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Concentration Heating System with Optical Fiber Supply

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Abstract

This paper reports on an experimental realization and field testing of a recently proposed solar fiber optic mini dish light concentrator connected to a hot water accumulator. The prototype dish is 150 cm 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 storage tank. This surface absorbs the radiation which remains trapped inside as it heat exchanges with tank fluid which temperature can reach 70°C.

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1. Introduction

Solar energy has for many centuries been harvested by various methods. Different types of solar collectors, normally producing hot water at temperatures between 30°C to 90°C, are commonly used. Large areas of mirrors are used to concentrate the solar heat to very high temperatures in order to drive boilers for production of electricity. The other main development is solar cells (photo-voltaic) for direct production of electricity. More recent development concerns the collection and transmission of visible light through optical fibers for direct illumination [1].

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Optical fibers now play an important part in the fields of both long distance telecommunications and short link networks (LAN's, etc.). More recently, designers have successfully applied less expensive, more mechanically robust fibers to various problems of illumination, such as safety lighting, background lighting, and medical lighting, among others. Typically, optical fiber for communications purposes uses glass fiber with very small core diameters. On the other hand, more recent development work has concentrated on improving the light-propagating properties of larger core diameter fiber made out of plastic [2].

In current study hot water production is achieved by a solar (light) collector (Fig.1a) from which the visible light is transported though an optical fiber (Fig.1b) to a water tank where the light dissipates into heat. Since light collectors have the advantage of low attenuation, and no losses in the conversion from light to heated water [3], it is an energy efficient way to produce hot water. The efficiency of conventional flat plate solar collectors means that approximately 60% of incident solar energy is collected and transformed into 60^{o}C water.

Fig.1a: A SOLUX collector without the protecting acrylic dome [1].

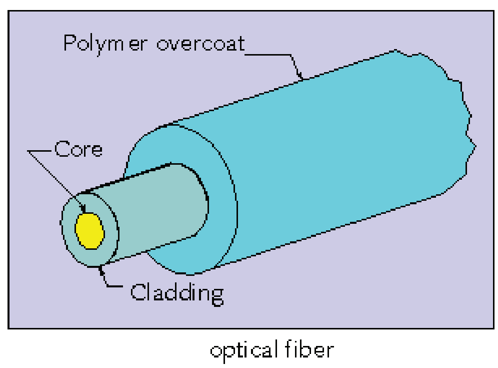

Fig.1b: Construction of optical fiber [6].

The objective of this study was to design a new light collector system for hot water production with considerably higher efficiency. The idea of carrying concentrated solar energy via optical fibers was first suggested in 1980 by a group of French researchers [4], [5], which reviewed performed work in this field, showed that experimental studies began more recently as summarized below:

- Khatri et al. (1993) discussed a solar energy collection system in which optical fibers are used to transport energy from a single-stage and a double-stage compound parabolic concentrator (CPC); [7]

- Liang et al. (1997) emphasized the high flux solar energy transmission by a flexible optical fiber bundle and the research on the associated CPC could greatly expand the existing field of solar energy concentrator applications; [8]

- Gordon et al. (2002a, 2002b) showed that optical fibers used to transport sunlight exhibit considerable light leakage within their nominal numerical aperture and this leakage depends on (i) the incidence angle, (ii) the optical properties of the core and the cladding and (iii) the fiber length; [9], [10]

- Kato et al, (1976) shows that the technology for optical fiber transmission offers a high quality production with a large diameter of the core; [11]

- Feuermann et al. (1998) in studying solar surgery used remote fiber-optic irradiation with highly concentrated sunlight in lieu of lasers. [12]

- Jaramillo et al. (1999) developed a theoretical thermal study of optical fibers transmitting concentrated solar energy; [13]

- Kribus et al. (2000) presented a study on the potential use of optical fibers for solar thermal power generation. The main performance characteristics (numerical aperture and attenuation) and typical costs of currently available fibers were discussed. [14]

2. Prototype concentrator design

The effective incoming radiation to the aperture plane is the beam radiation. An incident beam of solar radiation is a cone with an angular width of 0.53° [15]. The focal length is a determining factor in image size, and the aperture is the determining factor in total energy. It is assumed that the beam radiation is normal to the aperture and the reflection is specular and perfect. Each optical fiber has a pure transparent inner core and a thin transparent outer cladding. The total internal reflection allows us to guide the sunlight through the fiber. The fiber 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/admission angle of radiation θ_{max} at which total internal reflection occurs:

$$NA = \sin\theta_{max} = (n_1^2 - n_2^2)^2 \quad (1)$$

Here, NA is the numerical aperture. On the other hand, the energy rate Q_p hitting a flat receiver of a paraboloidal concentrator, where the optical fiber inlet is placed, is given by

$$Q_p = \pi f^2 (\sin^2\phi_r - \sin^2\phi_s)\rho_m G_b \quad (2)$$

Where f is the focal length, ρ_m is the reflectance of the surface, ϕ_r is the rim angle of the paraboloidal dish, ϕ_s is the shading angle because of the receptor size and Gb is the solar beam irradiance [16]. It is important to mention that the rim angle ϕ_r should be equal to or smaller than the optical fiber admission angle.

In optimum conditions, to ensure that the whole radiation gets into the fiber, the maximum rim angle (Fig.2) of the paraboloidal dish must be

$$\phi_r = \theta_{max} \quad (3)$$

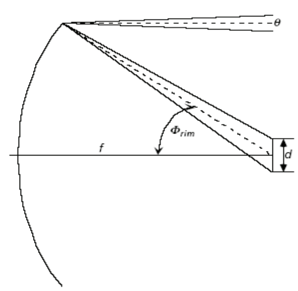

Fig. 2: Concentration of sunlight by a parabolic dish of focal length f and rim angle ϕ_r

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

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

For a flat receiver (at the focal plane of a paraboloidal concentrator) the receptor diameter D_r is given by

$$D_r = \frac{D_a \sin(0.267° + \delta/2)}{\sin\phi_r \cos(\phi_r + 0.267° + \delta/2)} \tag{5}$$

Where δ/2 is dispersion angle as a measure of the angular errors of the reflector surface and 0.267° is the half-angle of the incident beam cone of the solar radiation. It is important to indicate that the receptor diameter D_r should be equal to the diameter D_{0f} at the input section of optical fiber:

$D_{0f} = D_r$ (6)

Taking into account Eqs. (4) and (5), we can write the optimal focal length f_0 as

$$f_0 = \left(\frac{D_{0f}}{4\tan(\theta_{\max}/2)}\right)\left(\frac{\sin\theta_{\max}\cos(\theta_{\max} + 0.267° + \delta/2)}{\sin(0.267° + \delta/2)}\right) \tag{7}$$

The energy rate at the inlet of the optical fiber Q_p can be written as

$$Q_p = A_{0f}\,\rho_m\,G_b\,F_s\,C_{\max}, \tag{8}$$

$$F_s = \frac{\sin^2\theta_{\max} - \sin^2\phi_s}{4\tan^2(\theta_{\max}/2)}, \tag{9}$$

$$C_{\max} = \frac{A_a}{A_{0f}} = \frac{\sin^2\theta_{\max}\cos^2(\theta_{\max} + 0.267° + \delta/2)}{\sin^2(0.267° + \delta/2)}, \tag{10}$$

Where A_{0f} is the area of the input optical fiber, A_a is the aperture area of the paraboloidal mirror, C_{max} is the maximum ratio of geometrical concentration and F_s is the view factor for a flat receiver of paraboloidal mirror and both depend on θ_{max}. A radiative flux Q_i as high as possible can be obtained by the maximum value for θ_{max} from the view factor F_s and the maximum geometrical concentration C_{max} [5]:

$$F_s C_{\max} = g(\theta_{\max}) = \left(\frac{\sin^2\theta_{\max}}{4\tan^2(\theta_{\max}/2)}\right)\left(\frac{\sin^2\theta_{\max}\cos^2(\theta_{\max} + 0.267°)}{\sin^2(0.267°)}\right), \tag{11}$$

g_{max} is the combined expression of the view factor and concentration ratio (dimensionless).

At this point, we consider a perfect/ideal paraboloidal mirror with zero dispersion (δ/2=0) and for the shading angle $\phi_s = 0.$ (12)

To determine the maximum value for the admission angle θ_{max} and to obtain the maximum energy rate at inlet optical fiber, it can be set as

$$\frac{dg(\theta_{\max})}{d\theta_{\max}} = 0, \quad 0 < \theta_{\max} < 90,$$

We obtain $\theta_{\max} \approx 40°$, and $g_{max}(40°) = 8638$ (Kandilli et al.,2009). On the other hand, from the definition of decibel losses per unit length, η_{of} optical efficiency of optical fiber and the energy rate Q_0 at the end of the optical fiber can be expressed as:

$$\eta_{of} = \frac{Q_0}{Q_p} = 10^{-L\,dB_{loss}/10} \tag{13}$$

Where L is optical fiber length and dB_{loss} is the optical fiber attenuation. The optical efficiency of the collector system for the optimum value can be given as

$$\eta_{opt} = \rho_m 10^{-L\,dB_{loss}/10} F_s(\theta_{max}) \tag{14}$$

Where F_s is the view factor. Overall system efficiency can be expressed as

$$\eta_s = \frac{Q_0}{A_a G_b} \tag{15}$$

Maximum and minimum size of the image on the focal point given firstly by Gordon et al. was reconstructed by modifying the equations with dispersion angle. The diameter d_{min} of the approximately uniform-flux core region of the focal spot is

$$d_{\min} = 2D_a \left[\frac{1}{4\tan(\phi_r/2)} \right] \sin(0.267° + \delta/2) \tag{16}$$

The focal spot diameter d_{max} that accepts essentially all reflected rays is:

$$d_{\max} = \frac{D_a \left[1 + \frac{1}{\tan^2(\phi_r/2)} \right]^2 \sin(0.267° + \delta/2)}{2\left[\frac{1}{\tan^2(\phi_r/2)} - 1 \right] \left(\frac{1}{\tan(\phi_r/2)} \right)} \tag{17}$$

When designing for maximum flux concentration from the dish, the diameter of the optical fiber should be selected as d_{min} and for a maximum efficiency design the fiber diameter will be closer to d_{max}. Optical fibers with large numerical aperture, large core diameter and small attenuation should be used for effective transmission of concentrated solar energy.

3. Outline of Studied system

The studied light collector system for hot water production, which is outlined in Fig.3, contains:

- Light concentrator represented by a parabolic mirror that has the following geometrical characteristics: Diameter (D) = 1.5 m.
- Optical fiber SPCH 1000/1035/1400Z from Fiberguide company with:
    - Length = 2 m,
    - Silica core with a diameter of 1 mm,
    - Average attenuation $\tau = 6.2*10^{-3}$ dB/m on all solar spectrum,
    - Numerical aperture θf=20°.
- Cylindrical storage tank composed with:
    - Height = 1.5m ,
    - Volume = 0,15 m^3,

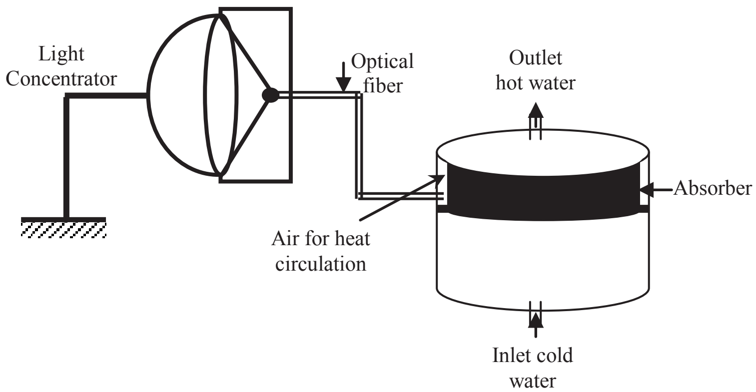

Fig.3: Light collector for hot water production and storage

Table1: Parameters of parabolic dish

Parameters		Parameters	
D_a (m)	1.5	C_{max}	1858
D_r (m)	0.035	NA	0.4
f (m)	0.88	g_{max}	8309
f_0(m)	0.9	d_{min} (m)	0.020
Φ_r (°)	46	d_{max} (m)	0.034
Φ_s (°)	0	ρ_m	0.85
θ_{max} (°)	45	η_{of} (%)	99.7
$\delta/2$	0.4	η_o (%)	61.7
dB_{loss} (dB/m)	$6.2*10^{-3}$	η_s (%)	61
L (m)	2		

Table 1 presents measured and calculated parameters of paraboloidal dish. The optical fiber used in the present study is the type SPCH 1000/1035/1400Z from Fiberguide Company. The length of optical fiber is 3m and the diameter is 0.001m. The maximum admission angle of optical fiber was determined by Eq. (1) and the rim angle of the dish by Eq. (4). The attenuation of the optical fiber is indicated as $6.2*10^{-3}$dB/m by the manufacturer data. The ideal transmission efficiency of the optical fiber was found to be 99.7%. For maximum concentration ratio, the rim angle was used in Eq. (10) and was found to be 1858.
In this case and using θ_{max} in Eq. (9) the view factor Fs was found to be 0.728. Consequently, optical efficiency of the whole system was calculated as 61.7% in optimum condition. Overall system efficiency was found to be 61% according to Eq. (15).

The size of the image has uniform flux as given by d_{min}. As indicated in Table 1, d_{min} was calculated as 2.0 cm according to Eq. (16). If the aim is to receive all flux concentrated on the focal point, it should be considered maximum image size. For the existing system, d_{max} was calculated as 3.4 cm by considering dispersion effects according to the Eq. (17).

The cylindrical storage tank is composed of four parts as shown in Fig.4.

- ***Part 1 :*** External wall of the tank made of galvanized steel(H=1.50m; D=0.60m)
- ***Part 2 :*** Thermal insulating foam with a height (H=1.55m; D=0.65m)
- ***Part 3 :*** Internal wall of tank made of galvanized steel (H=1.50m; D=0.50m)
- ***Part 4 :*** Absorber of galvanized steel with (H=0.50m; D=0.46m)

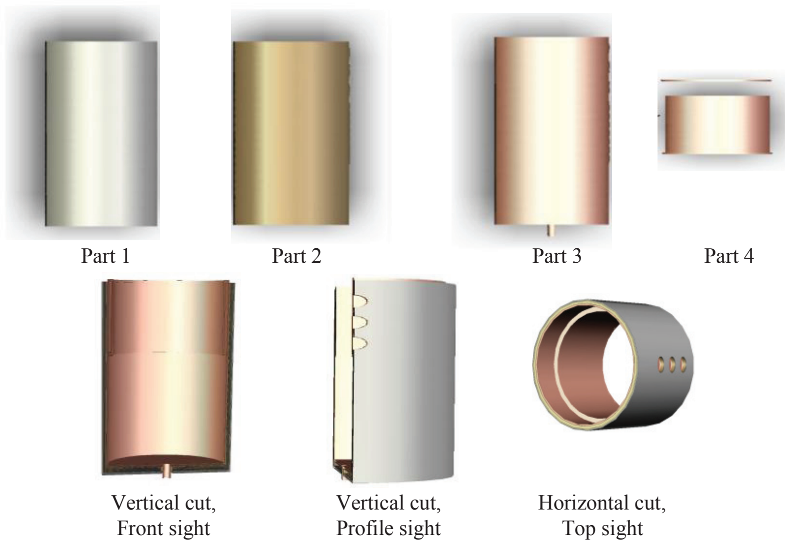

Fig.4: Description of how the cylindrical tank is assembled.

4. Experimental study of the prototype

After designing and assembling the two modules (concentrator + storage tank) (Fig.5), we undertook an experimental study.

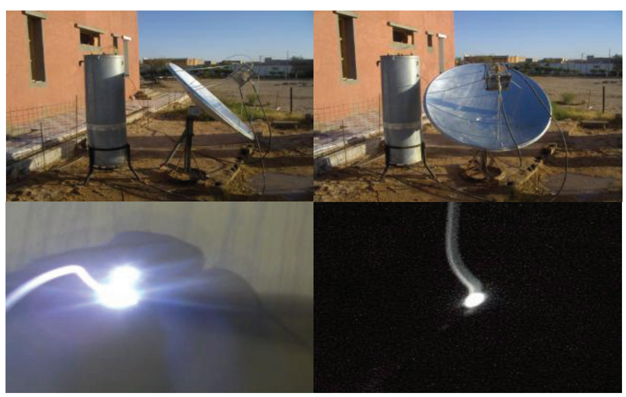

Fig.5: Photos of the designed system and sunlight in the optical fiber outlet

Practical considerations militate against large and small dish rim angles. At small rim angles, relatively high efficiency can be realized at peak concentration; but for a given fiber size, smaller diameter dishes must be used. Dish focal length is large relative to the diameter, which creates a practical problem in terms of module depth.

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

1. An absorptive loss in the dish mirror of 5%;
2. Fresnel reflective losses at the module glazing (3% with an AL coating);
3. Fresnel reflective losses at the fiber ends (a total of 5% with AL coatings);
4. Ray rejection in the secondary concentrator (in the range of 1 to 4% depending on the dish rim angle, and about 2% at ϕ =45°) [17];

5. Absorption in a remote second stage of about 2 to 4%, depending on ϕ (absorptive losses in a dielectric proximate second stage are negligible) (Welford and Winston, 1989)[17];

5. Results and discussion

Adrar city is located in south-west of Algeria, at 1600 km from Algiers capital, with a latitude of 27,88°, a longitude of -0.88° and an altitude of 270 m. It is characterized by particular climate conditions, i.e. hot and dry summers, cold and rigorous winters.

Any use of solar radiations must take into account the local and regional climatic conditions. It is widely known that all the observed atmospheric processes are the consequences of the received solar radiation. Thus, the measurement of the solar radiation presents special interest for the environmental researchers [18].

As shown in Fig.6, the great increase for whole radiations is located between February and March; and the maximum is obtained in July, with a slight stability for the global collector slope between March and October.

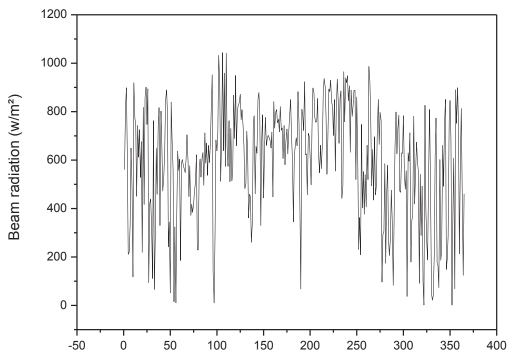

Fig.6: Hourly average solar beam radiation (W/m²)

Hourly global irradiance data of 2004 obtained meteorology stations were used to put forward the hourly normal beam radiation reaching the aperture plane of the paraboloidal dish. Global irradiance data were separated to beam and diffuse component by using the Clear Sky Model [Meteonorm]. The normal beam radiation calculated hourly was used to evaluate the monthly average hourly output power obtained from the paraboloidal dishes.

As shown in Fig.5, the great increase for whole radiations is located between February and March; and the maximum is obtained in July, with a slight stability for the global collector slope between March and October. These data were presented to estimate the output power of the system. And taking into account all the factors that reduce the system performance, we can determine with Eq.(8) and Eq.(13) the annual mean of the output power from optical fiber.

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 temperature in Fig.7 can reach 170°C at the equinoxes and 150°C at the solstice.

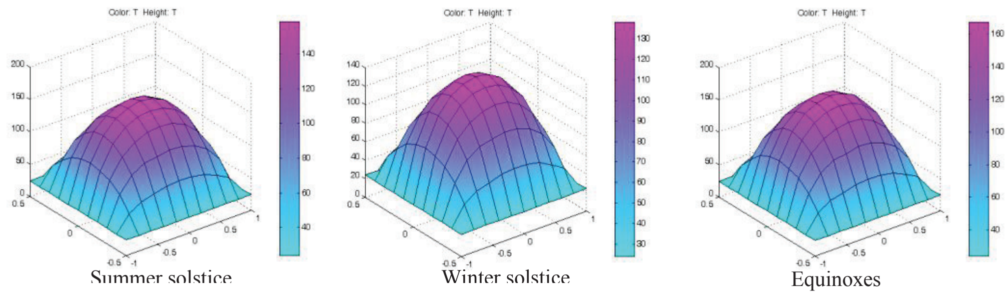

Fig 7: Temperatures reached on a selective surface at the solstices and the equinoxes

In performed tests the water flow rate through the accumulator tank was 0.6 l/min. Fig.7 shows the inlet and outlet temperature variation on 22 January 2009. Under the light of these results, we noted the existence of a gap in the beginning of the manipulation of over 10 °C which became 50 °C at noon. It took approximately four hours to fill the storage tank with a flow rate of 0.6 l/min to obtain an average daily temperature of 36.5 °C. The decreases observed in Fig.8 for the outlet temperature T_s are resulted by the manual sun tracking system.

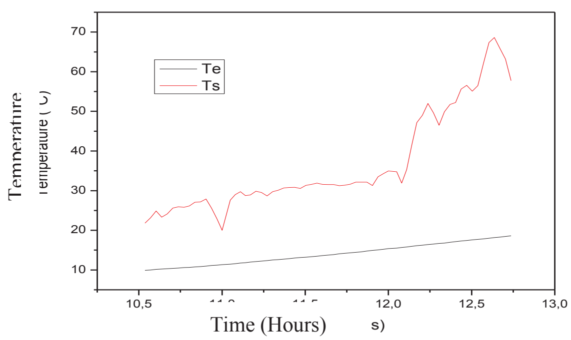

Fig.8: Measured water inlet and outlet temperatures, 22 Jan 2009.

6. Concluding remarks

The major finding of the current analysis is that the use of optical fibers in solar thermal concentrating systems for heating is technically feasible, under specific circumstances. In the first phase of our solar fiber-optic paraboloidal dish program the main conclusions of performed study are:

1. A solar fiber-optic heating system was designed, constructed and tested
2. Collection, concentration and transmission of sunlight were demonstrated.
3. The mathematical model of paraboloidal dish system was described.
4. The measured output power from the dish was evaluated against radiation data from the local meteorological station supplied by the Renewable Energy Research Unit (URER/MS) in Adrar.
5. Optimizing the receiver and dish sizes are important in order to maximize the system efficiency.
6. The calculated optical efficiency of the system was 62% at optimum conditions.
7. The calculated mean power from the paraboloidal dish was 885kW which for an aperture area of 1.7 m^2 means 520 kW/m^2.
8. The heat was stored in a 0.15 m^3 storage tank.
9. The temperature of outlet water from the storage tank reached 70^{o}C.

During the experimentation we encountered some difficulties e.g.

- Dust accumulation on the mirror and at the fiber tip.
- The parabolic mirror was made from a satellite dish which surface was clothed by a foil tape. Its aluminum plies reduced the reflectivity that meant extra energy loss.
- The optical fiber was aligned at the concentrator focus by placing a cone (Length=0.15m Diameter=0.075m) in the parabolic focus, mouthing the mirror. It was problematic to attach the fiber exactly at the focus.
- The manual measurements meant fewer measurements and more errors.
- Instead of using the desired optical fiber with relatively large diameter and high numerical aperture (NA), two optical fibers with a NA=0.4 manufactured by FiberGuide Company, USA, was used.

Current study showed that concentrated solar energy can be transferred as light by optical fibers to a selective surface (absorber) inside a storage tank, where the light is converted to heat. Such systems should have great potential in a wide range of solar energy applications.

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