THERMAL ANALYSIS OF A LINEAR FRESNEL LENS SOLAR COLLECTOR WITH BLACK BODY CAVITY RECEIVER

Iuliana SORIGA[1], Constantin NEAGA[2]

Tuburile vidate sunt printre cele mai utilizate captatoare pentru conversia termică a energiei solare. Această lucrare îşi propune să analizeze un astfel de captator, care foloseşte o soluție constructivă diferită de cele clasice, şi să compare performanța acestuia cu a captatoarelor comercializate în prezent. Acesta utilizează lentile liniare Fresnel pentru a concentra radiația solară pe un receptor cilindric tip cavitate. Suprafața interioară a tubului de sticlă este acoperită cu un strat reflectorizant. În consecință, majoritatea razelor care pătrund în cavitate sunt absorbite (principiul corpului negru).

Evacuated tubes are among the most common collectors used in solar thermal energy conversion. This paper aims to analyse such a collector that uses a different constructive solution than the classical, and compare its performance with other currently marketed collectors. The collector uses linear Fresnel lens to concentrate solar radiation on a cylindrical cavity receiver. The inner surface of the receiver's glass tube is coated with a reflective layer. Consequently, most of the rays that penetrate the tube are trapped inside the cavity (black body principle).

Keywords: solar thermal analysis, linear Fresnel lenses, solar thermal conversion, solar concentrating collector.

1. Introduction

In the last decades, solar energy has been increasingly used. Also, studies have been conducted for harnessing the sun's free and non-polluting energy, in many domains, on a large scale [1-3]. Among those, many studies turned their attention to solar energy conversion with linear Fresnel lenses (for both thermal and photovoltaic applications). Zhai [4] tested the thermal and optical efficiency for four types of cavity receptors with linear Fresnel lenses as concentrators.

In this study we calculate the efficiency of a solar collector with Fresnel lenses as concentrator and a different type of receiver, and compare it with that of

[1] Ph.D. student, Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, Romania, e-mail: iuliana.soriga@gmail.com
[2] Prof., Faculty of Mechanical Engineering and Mechatronics, University POLITEHNICA of Bucharest, Romania, e-mail: constantin_neaga@yahoo.com

a currently marketed collector, an evacuated tube with CPC (compound-parabolic concentrator).

2. Collector models

(a) Fresnel concentrator model

In the studied collector, sunlight is focused by a linear Fresnel lens on the receiver in order to heat the working fluid, in this case, water. The receiver consists of a copper "U" tube inside a glass vacuumed tube.

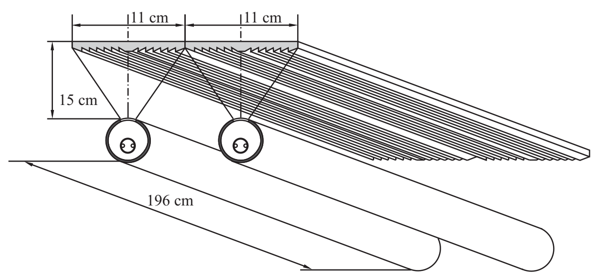


Fig. 1 Flat linear Fresnel lenses with absorbers.

The copper tube is surrounded by a cylindrical copper fin pressed on it, which has the role of increasing the absorber's area, resulting in improved heat transfer. The inner surface of the glass tube is coated with a highly reflective layer that sends the light to the copper fin. Unlike flat-plate collectors, it has the advantage of much lower heat loss due to the vacuum space between the absorber and the cylindrical glass tube.

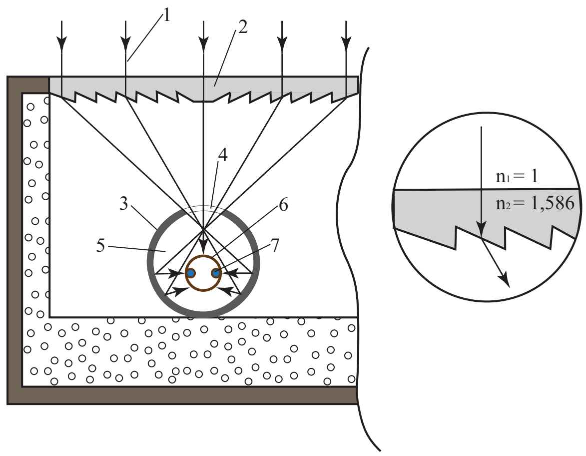


Fig. 2 Absorber detail and refraction through the linear Fresnel lens: 1 – sun rays; 2 – Fresnel lens; 3 – glass tube; 4 – linear transparent aperture; 5 – vacuum; 6 – absorber fin; 7 – copper U tube.

The lens considered in this study is a flat nonimaging Fresnel lens (Fig. 1) simetrically shaped, in order to redirect the solar rays on the absorber. The lens is manufactured of polycarbonate, which is high temperature resistant, and has a refractive index of 1.586.

Fig. 2 shows a cross section through the receiver and a detail of the solar radiation path. The solar rays, 1, that pass through the Fresnel lens, 2, are concentrated on the linear transparent glass tube aperture, 4. From here, the radiation is reflected through the vacuum environment, 5, by the inner surface of the glass on the absorber fin, 6. The energy transformed into heat is conducted by the fin to the copper U tube and finally absorbed by the water, 7.

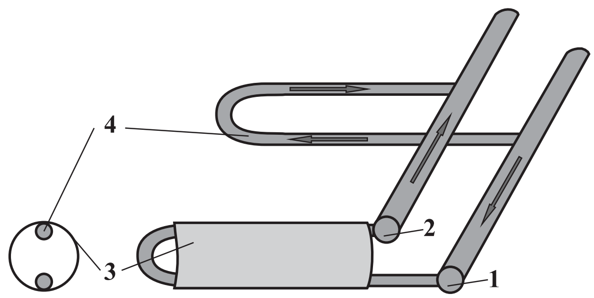


Fig. 3 Fluid flow in the collector: 1 – cold water inlet; 2 - hot water outlet; 3 – absorber fin; 4 – absorber pipe.

Fluid flow in the collector is represented in Fig. 3. The working fluid enters the collector inlet pipe, 1, then it is evenly distributed to the “U” tubes, 4, absorbs heat, and, in the end, it is accumulated again in the outlet pipe, 2.

(b) CPC concentrator model

The CPC collector (Fig. 4) has a similar absorber with the previous one. The similarity consists in the fact that here also, a copper U tube is surrounded by

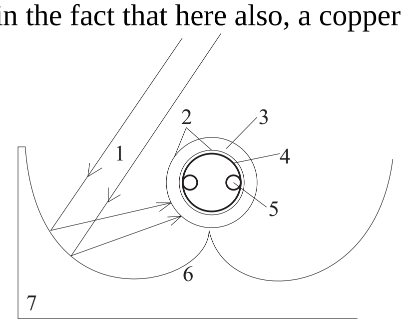


Fig. 4 Evacuated tube with CPC collector: 1 – sun rays; 2 – inner and outer glass tubes; 3 – vacuum; 4 – absorbing fin; 5 – copper U tube; 6 – cpc concentrator; 7 – collector case.

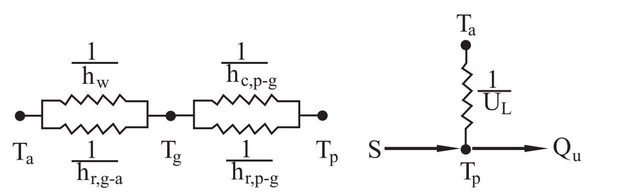
a copper fin. The difference is that there are two glass tube layers and the concentrator is not a flat lens, but a compound-parabolic reflector. The vacuum is in this case between the two glass layers. Part of the solar radiation falls directly on the receiver surface, while the rest is reflected by the CPC on the outer glass tube. The outer glass tube transmits the rays to the inner glass tube, which conducts the energy to the absorber fin. From here, the process is identical to the one in the previous collector. The fluid flow is also the same, as shown in Fig. 3.

3. Analysis

In order to simplify the calculations, the following assumptions were made:

- system properties are constant (heat transfer coefficients, water specific heat capacity, etc.);
- solar energy absorbed by the glass is neglected;
- radiant flux is uniformly distributed on the fin surface;
- heat loss through the back side of the collector is neglected;
- the system is operating under steady state conditions.

Thermal resistances in accordance with the above assumptions are shown in Fig. 5.



Heat transfer Equivalent thermal network

Fig. 5 Heat transfer in the collector.

For the thermal analysis of the studied collector the following formulae have been used [5]:

Collector efficiency:

$$\eta = \dot{m}\, c_p \left(T_{in} - T_{out}\right) / \left(S \cdot A_c\right), \tag{1}$$

The heat flux absorbed by the working fluid:

$$Q_u = S - Q_L \text{, W/m}^2, \tag{2}$$

Energy losses:

$$Q_L = U_L \left(T_p - T_a\right) \text{, W/m}^2, \tag{3}$$

Overall heat loss coefficient:

$$U_L = U_t + U_e \text{, W/(m}^2\text{·K)}, \tag{4}$$

Edge loss coefficient:

$$U_e = (UA)_{edge} / A_c \text{,W/(m}^2\text{·K).} \quad (5)$$

Top loss coefficient:

$$U_t = \left(\frac{1}{h_{c,p-g} + h_{r,p-g}} + \frac{1}{h_w + h_{r,g-a}} \right)^{-1} \text{,W/(m}^2\text{·K),} \quad (6)$$

where, $h_{c,p-g}$ is the convection heat transfer coefficient from the glass tube to pipe, W/(m^2·K), $h_{r,p-g}$ - radiation heat transfer coefficient from the glass tube to pipe, W/(m^2·K), h_w - convection heat transfer coefficient from the glass tube to the environment, W/(m^2·K), $h_{r,g-a}$ - radiation heat transfer from glass tube to ambient, W/(m^2·K).

Radiation heat transfer coefficient [6] between two cylinders:

$$h_{r,p-g} = \sigma\left(T_p + T_g\right)\left(T_p^2 + T_g^2\right) / \left[\frac{1}{\varepsilon_p} + \frac{d_p}{d_g}\left(\frac{1}{\varepsilon_g} - 1 \right) \right] \text{,W/(m}^2\text{·K),} \quad (7)$$

where, σ - Stefan-Boltzmann constant, 5.67 x 10^{-8} W/(m^2·K^4), T_g - glass cover temperature, K, ε_p – copper pipe emissivity, ε_g – glass cover emissivity, d_p, d_g – plate outer and glass tube inner diameter.

Convection heat transfer coefficient from the glass tube to the environment [7]:

$$h_w = \frac{8{,}6 \cdot v^{0{,}6}}{L^{0{,}4}} \text{,W/(m}^2\text{·K),} \quad (8)$$

where, v is wind speed, L - collector length.

Radiation heat transfer coefficient between the glass cover and the environment:

$$h_{r,g-a} = \varepsilon_g \cdot \sigma\left(T_g + T_{sky}\right)\left(T_g^2 + T_{sky}^2\right) \text{,W/(m2·K),} \quad (9)$$

where, T_{sky} is the sky temperature [8], $T_{sky} = T_a - 6$, K.

For both the Fresnel collector and the evacuated CPC, the finite difference method was implemented in Matlab, in order to obtain temperature variation along the copper U tube. In this case, the absorber fin was considered rectangular. Abdel-Khalik developed analytical equations for heat flow behavior in a serpentine collector. A finite difference technique [9], derived from these equations, was used to perform the thermal analysis of the fin and tube (Fig. 6).

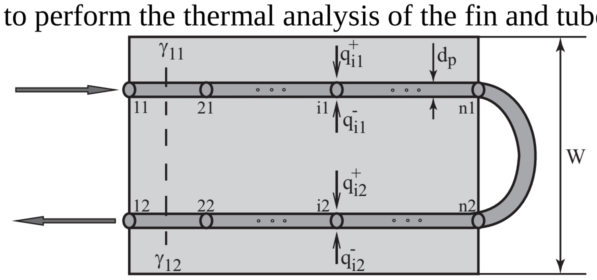


Fig. 6 Finite difference technique.

The analytical equations for the heat flow per unit length entering the base of the tube are presented in equations (10) to (13):

$$q_{ij}^{+} = \kappa\left[\theta_{(i-1)j} - \theta_{ij}\cosh m\right], \tag{10}$$

$$q_{ij}^{-} = \kappa\left[\theta_{(i+1)j} - \theta_{ij}\cosh m\right], \tag{11}$$

$$q_{11}^{+} = \kappa\theta_{11}\left(1-\cosh m\right), \tag{12}$$

$$q_{12}^{-} = \kappa\theta_{12}\left(1-\cosh m\right), \tag{13}$$

where,

$$\theta_{ij} = T_{bij} - T_a - S/U_L, \tag{14}$$

$$\kappa = \frac{k\delta m}{\left(W-d_p\right)\sinh m}, \tag{15}$$

$$m = \left(W-d_p\right)\sqrt{U_L/k\delta}, \tag{16}$$

In the above equations, q_{ij}^{+} and q_{ij}^{-} represent the heat received by the i^{th} element of the j^{th} part of the tube from left and right side (i is the number of elements on the longitudunal direction and j is the number of pipe turns; $1 \le j \le 2$, $1 \le i \le n$). For the first element the heat has been calculated according to equations (12) and (13). Also, δ is the fin thickness, m, k is the fin conductivity, W/(m·K), and W represents the fin width, m.

The total useful heat gained by an element:

$$q_{useful} = q_{ij} - d_p U_L \theta_{ij} = \frac{T_{bij} - T_{fij}}{R}, \tag{17}$$

$$R = \frac{1}{C_b} + \frac{1}{\pi d_i h_{fi}}, \tag{18}$$

$$q_{ij} = q_{ij}^{+} + q_{ij}^{-}, \tag{19}$$

where, T_{bij} is the temperature at the pipe base, K, T_{fij} is the fluid temperature, K, R is the thermal resistance, C_b is the conductivity between the pipe and the fin, W/(m·K), d_i is the pipe inner diameter, m, and h_{fi} the convection heat transfer coefficient for the working fluid, W/(m^2·K).

The total heat transferred to each node:

$$\dot{m}\, c_p \left(\gamma_{11} - T_{11}\right) = q_{11} \frac{\Delta y}{2}, \tag{20}$$

$$\dot{m}\, c_p \left(\gamma_{(i+1)j} - \gamma_{ij}\right) = q_{(i+1)j} \Delta y, \tag{21}$$

$$\dot{m}\, c_p \left(T_{12} - \gamma_{12}\right) = q_{12} \frac{\Delta y}{2}, \tag{22}$$

where, *γ* represents the medium temperature, K, and *Δy* is the distance, m, between two nodes.

$$\frac{\gamma_{ij} + \gamma_{(i+1)j}}{2} = T_{(i+1)j}, \tag{23}$$

As a boundary condition, temperature in node *n1* was considered equal to the temperature in node *n2*.

$$\frac{\gamma_{(n-1)1} + \gamma_{(n-1)2}}{2} = T_{n1} = T_{n2}. \tag{24}$$

$$\dot{m}\, c_p \left(\gamma_{(n-1)2} - \gamma_{(n-1)1}\right) = \left(q_{n1} + q_{n2}\right)\Delta y, \tag{25}$$

The properties for both collectors are presented in Table 1. As we have specified before, the dimensions are identical, in order to have a reliable comparison between the two.

Table 1

Collectors specifications

Component	Fresnel	CPC	Parameters	Value	Unit
Glass tube	Lens	Outer glass tube	Transmissivity	0,92	
			Absorptivity	0,02	
			Conductivity	1,2	W/(m·K)
	Case dimensions		Length	1920	mm
			Width	660	mm
Absorber	Copper U tube		Inner diameter	5,5	mm
			Outer diameter	6	mm
	Absorber fin		Absorptivity	0,92	
			Emissivity	0,08	
			Conductivity	401	W/(m·K)

4. Results

Four cases were studied: summer, winter, clear and cloudy sky. The maximum and minimum solar radiation intensity values were considered for a June day (summer case), respectively a December day (winter case). The exact values are [10]: summer sunny 905 W/m^2, summer cloudy 462 W/m^2, winter sunny 140 W/m^2, winter cloudy 68 W/m^2. Results show that the studied collector has a higher efficiency compared to the evacuated CPC in terms of useful heat extracted from solar radiation.

In order to compare the efficiencies, curves have been drawn for different fluid inlet temperatures and different fluid flows, for both CPC and linear Fresnel collector. Fig. 7 illustrates the thermal efficiency variation with the temperature difference between the fluid mean temperature and the ambient temperature divided by the solar irradiance, in clear sky summer conditions (905 W/m^2). It can be seen that the efficiency decreases with temperature increase, which is understandable because at higher temperatures the fluid heat storage capacity is lower. This also causes an increase in heat losses, which cause the efficiency decrease. The difference between the efficiencies of the two collectors is about 3% in the summer sunny case and reduces to about 1% for winter sunny case (462 W/m^2), Fig. 8.

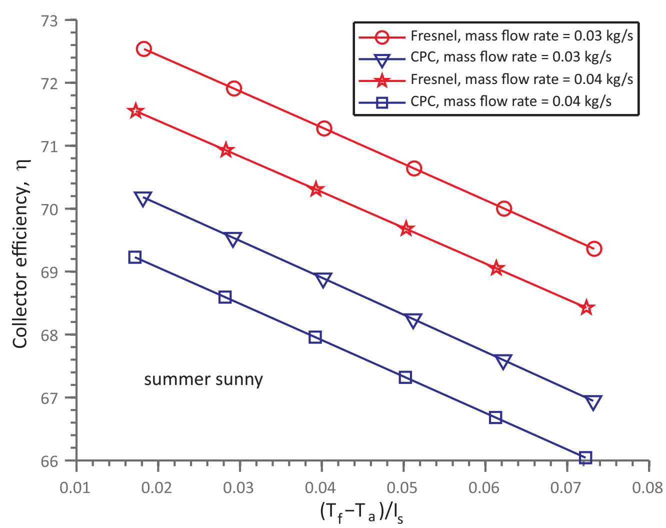


Fig. 7 Effect of fluid temperature on efficiency

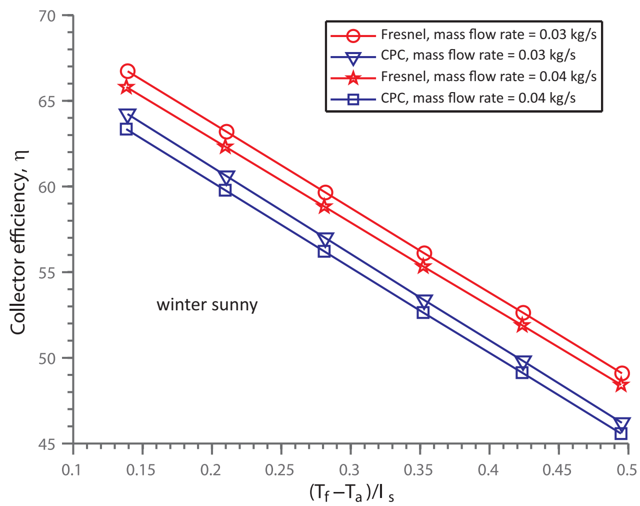


Fig. 8 Effect of fluid temperature on efficiency

Fig. 9 and Fig. 10 show the temperature difference (between inlet and outlet from the U tube) variation with inlet temperature. The inlet temperature variated between 10 and 70 degrees Celsius for the summer case, and between 10 and 50 degrees Celsius for the winter case. The working fluid mass flow rate was considered in both cases 0.04 kg/s. The same as in the previous two figures, the values for the CPC are less than for the Fresnel collector. Fig. 9 shows the results for the summer conditions. The difference is approximately 0.3 degrees in the sunny case and 0.1 in the cloudy case. In the winter conditions, Fig. 10, the difference is even smaller, aproximately 0.13 degrees for sunny and 0.06 degrees for the cloudy case.

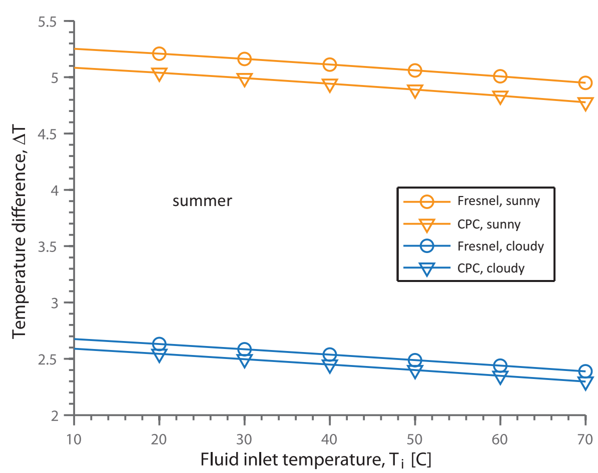


Fig. 9 Temperature difference variation with inlet fluid temperature

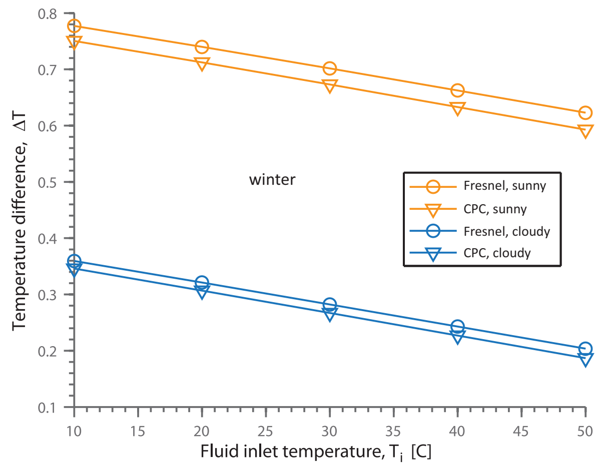


Fig. 10 Temperature difference variation with inlet fluid temperature

For the finite difference analysis, six nodes have been considered on the longitudinal direction (*n* = *6*). Because the fluid circulates inside a "U" tube, there is only one pipe turn, meaning that it was divided in twelve elements. In the summer case the fluid inlet temperature was considered 30 degrees Celsius, and in the winter case 10 degrees Celsius. The working fluid temperature variation in the summer sunny case, along the copper pipe length is shown in Fig. 11. It can be seen that the outlet temperature for Fresnel collector is slightly higher than for the CPC. The same is true for winter sunny, Fig.12. Also, for the larger mass flow rate (0.04 kg/s) the temperature difference is smaller.

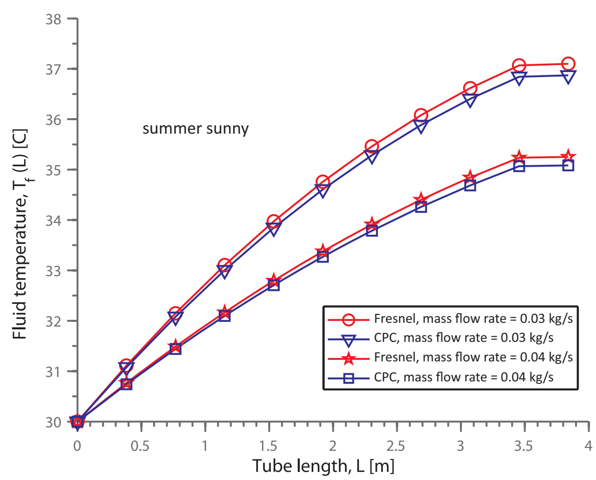


Fig. 11 Fluid temperature variation with tube length

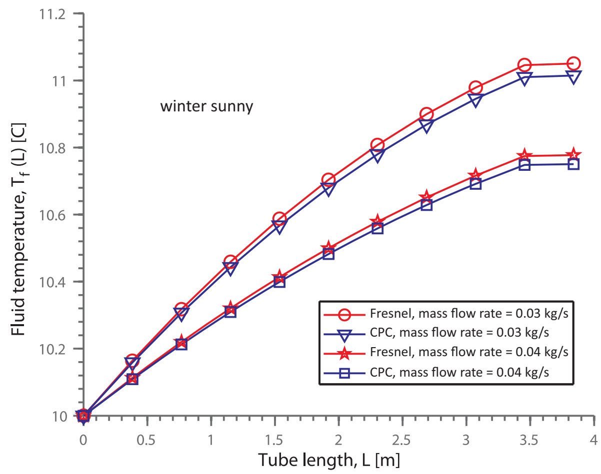


Fig. 12 Fluid temperature variation with tube length

5. Conclusions

In this paper, the thermal analysis of the linear Fresnel lens solar collector with black body cavity receiver has been performed. In order to calculate the efficiency of this collector, a mathematical model was implemented in Matlab. The finite difference method – also implemented in Matlab – was used to determine the water temperature along the pipe length. It has been shown that among the environmental and the operational factors, the design parameters also influence the collector performance. In this case, a higher value for the efficiency of the Fresnel collector was observed, when compared to the evacuated CPC with the same type of receiver. Although the graphs clearly show the superiority of the Fresnel collector, to complete this analysis, an economic study should be conducted, in order to determine it’s profitability and feasibility. This is our objective in the near future.

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R E F E R E N C E S

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