COBEM2015

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

SOLAR IRRADIANCE OPTIMIZATION FOR APPLICATION IN LINEAR FRESNEL COLLECTORS

Gabriel da Silva Lima
Federal University of Rio Grande do Norte, Mechanical Engeneering, University Campus, Lagoa Nova 59078970, Natal, RN, Brazil.
limagabriel@bct.ect.ufrn.br
Gabriel Ivan Medina Tapia
Federal University of Rio Grande do Norte, Mechanical Engeneering, University Campus, Lagoa Nova 59078970, Natal, RN, Brazil.
gmedinat@ct.ufrn.br

Abstract. *The development of technologies for the benefit of solar energy has been outstanding in recent years due to its enormous potential use for generating electricity. Among these technologies highlights the Concentrated Solar Power (CSP) that concentrate the solar radiation to a specific point. Because of the concentrators are subject to seasonal variation of solar irradiation is of great importance the development of mathematical models to calculate this energy. This work, more precisely, proposes a technique for calculating the amount of solar energy that optimizes the operating time of solar concentrators, particularly the Linear Fresnel Reflectors (RFL). The technique is to establish an algorithm for direct normal irradiance calculation purposes taking into account the thermal analysis of the energy losses associated with the operation of this type of system. The model to be applied to climate conditions of the city of Natal/Brazil, but can also be used for other parts of the world.*

Keywords: *Concentrated Solar Power, Direct Normal Irradiance, Linear Fresnel reflector*

1. INTRODUCTION

Concentrated solar power (CSP) collectors are panels that capture the sun's radiation and redirect to a single point. They can take different formats in which we can detach the Cylindrical Parabolic Concentrator (CPC), Parabolic Disc (PD), Linear Fresnel Reflector (LFR), Central Tower (CT), among others.

In the case of LFR a set of plane mirrors turn direct the solar radiation to a central receiver. In the pipes installed within these receptors circulates a fluid, which can be water, which receives energy from solar radiation increasing its temperature and can be used to move a turbine in a Rankine cycle.

Depending on the application required, the CSP technology can provide a wide range of capacity in power generation ranging from a few kV to 50 MW (Fernandez-Garcia *et al.*, 2010). The use of synthetic or organic oil has been widely used as working fluid because of its low cost (Purohit *et al.*, 2013). However, the use of molten salt as working fluid gives higher temperatures allowing to the turbine to operate more efficiently (Desai *et al.*, 2014).

For the optimization of concentrated solar energy systems a number of parameters must be analyzed, among them stands out direct normal irradiance (DNI) (Desai *et al.*, 2014). The direct normal irradiance corresponds to the energy variation rate that focuses per unit area (W/m^2).

Due to variation DNI throughout the day and seasons, determine the amount of captured radiation is essential for design, as this will determine how much energy can be produced by a system utilizing solar concentrators.

In this work, first will be held a thermodynamic analysis of a LFR field and will apply the theoretical concepts developed to make a simulation for the city of Natal/Brazil.

2. THERMODYNAMIC ANALYSIS

In the Fig. 1 the system scheme is presented in analysis.

By Canavarro (2010) we see that the efficiency of a solar collector is given by,

$$\eta_{col} = \frac{\text{Heat rate utilized in the receiver}}{\text{Heat rate incident in the collector}} = \frac{\dot{Q}_{gain}}{\dot{Q}_{inc}} \tag{1}$$

As the heat rate utilized in the receiver is the difference between the heat rate absorbed by the receiver ($\dot{Q}_{abs,rec}$) and the heat rate lost in the receiver ($\dot{Q}_{los,rec}$), and the heat rate incident in the collector is given by the product between the irradiance in the design (I_D) and the solar collector area,

$$\eta_{col} = \frac{\dot{Q}_{abs,rec} - \dot{Q}_{los,rec}}{I_D \cdot A_p} \tag{2}$$

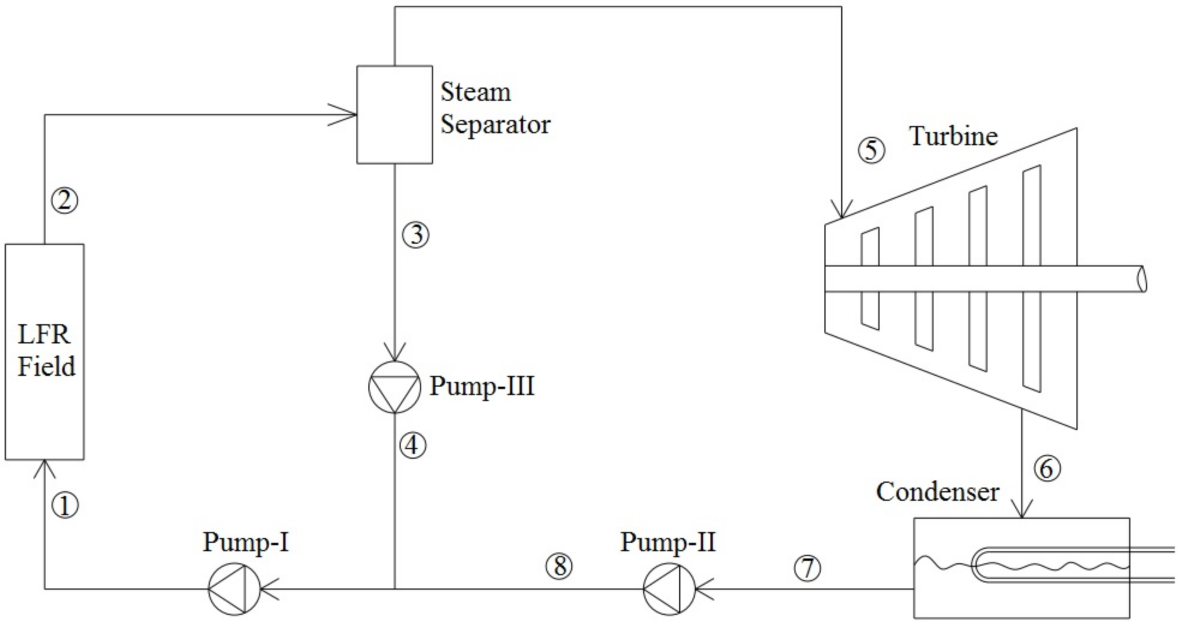

Figure 1. Scheme of a LFR system

By Stine and Geyer (2001), we have the definition of optical efficiency given by:

$$\eta_{ot} = \frac{\text{Heat rate absorbed by the receiver}}{\text{Heat rate incident in the collector}} = \frac{\dot{Q}_{abs,rec}}{\dot{Q}_{inc}} = \frac{\dot{Q}_{abs,rec}}{I_D \cdot A_p} \tag{3}$$

The heat loss rate at the receiver is proportional to the product of the collector area and the temperature difference $(T_m - T_\infty)$, being T_m average temperature between the temperatures before and after the receiver and T_∞ the ambient temperature. The proportionality constant μ_L is called loss coefficient based on the collector area.

$$\eta_{col} = \eta_{ot} - \mu_L \cdot \frac{T_m - T_\infty}{I_D} \tag{4}$$

From energy balance in the system, Fig. 1 along with Eq. (1) found,

$$\dot{Q}_{gain} = \dot{m}_D \cdot (h_2 - h_1) = \eta_{col} \cdot I_D \cdot A_p \tag{5}$$

From Eqs. (4) and (5),

$$\dot{m}_D = \left(\frac{\eta_{ot} \cdot I_D}{\Delta h} - \frac{\mu_L \cdot \Delta T}{\Delta h} \right) \cdot A_p \tag{6}$$

Doing the same procedures for the real case, being I the real irradiance,

$$\dot{m} = \left(\frac{\eta_{ot} \cdot I}{\Delta h} - \frac{\mu_L \cdot \Delta T}{\Delta h} \right) \cdot A_p \tag{7}$$

In the system, Fig. 1, disregarding losses in the pumps I, II and III and from energy balance we found,

$$\dot{Q}_{gain} = \dot{m}_{cl} \cdot (h_2 - h_1) = \dot{m}_{t,c} \cdot (h_5 - h_7) \tag{8}$$

From Eq. (8) and (5), being η the real collector efficiency,

$$\dot{m}_{t,c} \cdot (h_5 - h_7) = \eta \cdot I \cdot A_p \tag{9}$$

From conservation of mass and energy in the control volume defined by points 1, 3 and 7 we find,

$$\dot{m}_3 + \dot{m}_7 = \dot{m}_1 \tag{10}$$

$$\dot{m}_3 \cdot h_3 + \dot{m}_7 \cdot h_7 = \dot{m}_1 \cdot h_1 \tag{11}$$

Dividing the Eq. (11) by $\dot{m}_1$,

$$\frac{\dot{m}_3}{\dot{m}_1} \cdot h_3 + \frac{\dot{m}_7}{\dot{m}_1} \cdot h_7 = h_1 \tag{12}$$

Denominating $\dot{m}_7/\dot{m}_1$ of dry output fraction of the working fluid, and denoting by x, the Eq. (12) can be written with a combination of Eq. (10) as,

$$h_1 - h_3 = x \cdot (h_7 - h_3) \tag{13}$$

$$h_1 = (1 - x) \cdot h_3 + x \cdot h_7 \tag{14}$$

Similarly, the conservation of mass and energy balance in the volume control of the region between points 2, 3 and 5:

$$\dot{m}_3 \cdot h_3 + \dot{m}_5 \cdot h_5 = \dot{m}_2 \cdot h_2 \tag{15}$$

As $\dot{m}_2 = \dot{m}_1$ and $\dot{m}_5 = \dot{m}_7$, dividing them for $\dot{m}_1$,

$$(1 - x) \cdot h_3 + x \cdot h_5 = h_2 \tag{16}$$

A linear relation can be obtained between steam flow rate and power output of turbine through the Willan's line equation[1]:

$$\dot{W} = a + b \cdot \dot{m} \tag{17}$$

And the output power in the design is given by:

$$\dot{W}_D = a + b \cdot \dot{m}_D \tag{18}$$

Assuming a power loss y against the rated output of the turbine:

$$a = -y \cdot \dot{W}_D \tag{19}$$

Combining the Eqs. (17) and (18) with the Eq. (19) we found,

$$\dot{W}_D - \dot{W} = b \cdot (\dot{m}_D - \dot{m}) \tag{20}$$

In Eq. (6) and (7) doing,

$$\alpha = \frac{\eta_{ot}}{\Delta h} \tag{21}$$

$$\beta = \frac{\mu_L \cdot \Delta T}{\Delta h} \tag{22}$$

we found,

$$\dot{m}_D = (\alpha I_D - \beta) \cdot A_p \tag{23}$$

$$\dot{m} = (\alpha I - \beta) \cdot A_p \tag{24}$$

Combining the Eq. (23) and Eq. (24) with Eq. (20):

$$\dot{W}_D - \dot{W} = b \cdot (\alpha I_D - \beta) \cdot A_p - b \cdot (\alpha I - \beta) \cdot A_p$$

$$\dot{W}_D - \dot{W} = b \cdot \alpha \cdot (I_D - I) \cdot A_p$$

$$\dot{W}_D - \dot{W} = \tau \cdot (I_D - I) \cdot A_p \tag{25}$$

In which,

$$\tau = b \cdot \alpha \tag{26}$$

For the project is considered that the power turbine is the output power of P_D. In the analysis are disregarded kinetic energy and potential variations in the turbine, so the isentropic efficiency of the turbine can be calculated by Eq. (27),

$$\eta_{is} = \frac{\dot{W}_D}{\dot{m}_D \cdot \Delta h_{is}} \tag{27}$$

Combining the Eqs. (18) and (19), we found,

$$\dot{W}_D = -y \cdot \dot{W}_D + b \cdot \dot{m}_D$$

[1]The Willan's line is given by a linear approximation on a graph "steam consumption versus output power" for a steam turbine. The parameters a and b match lost power due to internal losses in W, and the slope of the curve in J/kg, respectively.

$$\dot{W}_D = \frac{b \cdot \dot{m}_D}{1+y} \tag{28}$$

Combining with the Eq. (26),

$$\dot{W}_D = \frac{\tau \cdot \dot{m}_D}{\alpha \cdot (1+y)} \tag{29}$$

From the Eqs. (23) and (29),

$$\frac{\dot{W}_D}{A_p} = \frac{\tau \cdot (\alpha I_D - \beta)}{\alpha \cdot (1+y)} = \alpha' \cdot I_D - \beta' \tag{30}$$

Being,

$$\alpha' = \frac{\tau}{1+y} \tag{31}$$

and,

$$\beta' = \frac{\tau \cdot \beta}{\alpha \cdot (1+y)} \tag{32}$$

In the period of time dt the turbine loses power $P_D - P$, that is, the expression $(P_D - P) \cdot dt$ charge differential loss in the turbine. The total loss L, per unit area, can be calculated from the following equation,

$$L = \int \frac{(\dot{W}_D - \dot{W})}{A_p} dt \tag{33}$$

or, using the Eq. (25):

$$L = \int \tau \cdot (I_D - I) \cdot dt \tag{34}$$

The Eq. (34) shows that the losses are proportional to the difference between the irradiance received on the project and the real. We should emphasize that this interval dt does not match an operating time interval, but a difference between the turbine operating times. It is worth noting the irradiance in the reflector lower will be the time required operation to achieve a certain energy to be used.

If the design is provided for a given irradiance I_D to be captured then a run time will be required t_D to the turbine. We will also take into account that there is a minimum irradiance (I_c) that the system can take advantage at a time turbine operating limit (t_c). Adopting the operating time as a function of irradiance ($t = f(I)$) the total loss in the turbine is expressing by:

$$L = \int_{f(I_D)}^{f(I_c)} \tau \cdot (I_D - I) \cdot dt \tag{35}$$

The integral of Eq. (35) is proportional to the hatched area in Fig. 2, so we can rewrite Eq. 35 as,

$$L = \int_{I_c}^{I_D} \tau \cdot (f(I_c) - f(I)) \cdot dI \tag{36}$$

The integral of Eq. (35) is proportional to the hatched area in Fig. 2, so we can rewrite Eq. 35 as,
Considering τ and $f(I_c)$ constants:

$$L = \tau \cdot \left(f(I_c) \cdot (I_D - I_c) - \int_{I_c}^{I_D} f(I) \cdot dI \right) \tag{37}$$

The output energy per unit area, the project is,

$$E_D = \frac{\dot{W}_D}{A_p} \cdot f(I_c) \tag{38}$$

The total effective power output (E) is given by:

$$E = E_D - L = \frac{\dot{W}_D}{A_p} \cdot f(I_c) - \tau \cdot \left(f(I_c) \cdot (I_D - I_c) - \int_{I_c}^{I_D} f(I) \cdot dI \right) \tag{39}$$

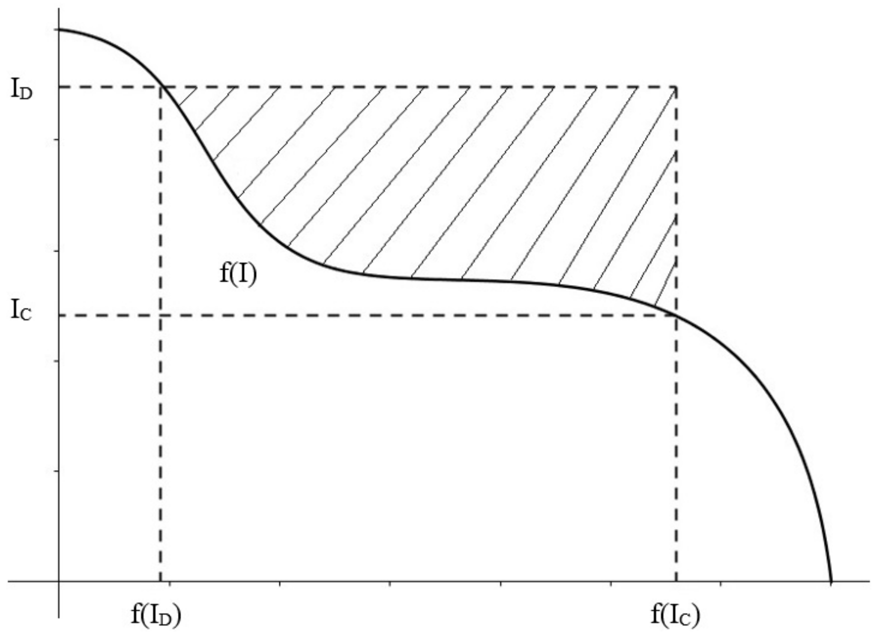

Figure 2. Irradiance *versus* operating time

Using the Eq. (30):

$$E = (\alpha' \cdot I_D - \beta') \cdot f(I_c) - \tau \cdot \left(f(I_c) \cdot (I_D - I_c) - \int_{I_c}^{I_D} f(I) \cdot dI \right) \tag{40}$$

Making the first and second derivative with respect to the expected irradiance (I_D):

$$\frac{dE}{dI_D} = \alpha' \cdot f(I_c) - \tau \cdot f(I_c) + \tau \cdot f(I_D) \tag{41}$$

$$\frac{d^2E}{dI_D^2} = \tau \cdot f'(I_D) \tag{42}$$

To find the critical points, Eq. (41) results in,

$$\alpha' \cdot f(I_c) - \tau \cdot f(I_c) + \tau \cdot f(I_D) = 0 \tag{43}$$

$f(I_D)$ is the expected operating time for the highest value of I_D captured. That is,

$$f(I_{D,max}) = \frac{\tau - \alpha'}{\tau} \cdot f(I_c) \tag{44}$$

Using the Eq. (31),

$$f(I_{D,max}) = \frac{y}{1+y} \cdot f(I_c) \tag{45}$$

For a minimum irradiance (critical) absorbed we will have a minimum power of the turbine operation ($\dot{W}_{min}$). Using Eq. (25) found,

$$\dot{W}_D - \dot{W}_{min} = \tau \cdot (I_D - I_c) \cdot A_p \tag{46}$$

From the Eq. (28) and using the relation of $\tau = b \cdot \alpha$,

$$\tau = \alpha \cdot \frac{\dot{W}_D \cdot (1+y)}{\dot{m}_D} \tag{47}$$

Combining the Eqs. (46) and (47),

$$\dot{W}_D - \dot{W}_{min} = \alpha \cdot \frac{\dot{W}_D \cdot (1+y)}{\dot{m}_D} \cdot (I_D - I_c) \cdot A_p \tag{48}$$

or,

$$I_c = I_D - \frac{(\dot{W}_D - \dot{W}_{min}) \cdot \dot{m}_D}{\alpha \cdot \dot{W}_D \cdot A_p \cdot (1+y)} \tag{49}$$

From the Eqs. (23) and (49),

$$I_c = I_D - \frac{(\dot{W}_D - \dot{W}_{min}) \cdot (\alpha I_D - \beta)}{\alpha \cdot \dot{W}_D \cdot (1+y)} \tag{50}$$

or,

$$I_c = I_D - \frac{\left(1 - \frac{\dot{W}_{min}}{\dot{W}_D}\right) \cdot (\alpha I_D - \beta)}{\alpha \cdot (1+y)} \tag{51}$$

3. RESULTS OF THE NUMERICAL SIMULATION OF SYSTEM

In the simulation used the clear sky model described in Duffie and Beckman (2013) and data presented in Desai *et al.* (2014).

From the data of Tab. 1 and equations deduced in the previous sections can obtain the value of I_D shown in Fig. 3.

Table 1. Data for simulation (Desai *et al.*, 2014)

Optical efficiency, η_{ot}	0.6
Loss coefficient, μ_L	0.2 W/m^2K
Dry output fraction, x	0.5
Turbine inlet temperature, T_5	$250,4\,°C$
Inlet pressure turbine, P_5	40 bar
Inlet pressure in the collector, P_1	45 bar
Loss fraction of the turbine, y	0.2
Coefficient of the equation Willans, b	686 kJ/kg
Ambient temperature, T_∞	$30\,°C$

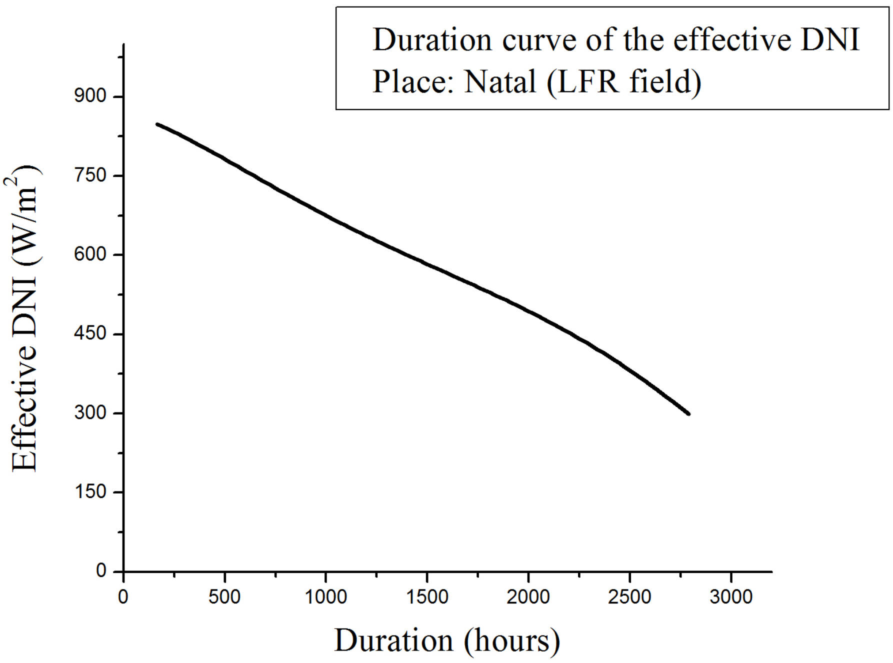

Figure 3. The duration curve of effective DNI for LFR field

The developed algorithm follows the following sequence:

1. Calculate the amount of ΔT from known states before and after the collector. The temperature variation is the subtraction between the mean temperature in the collector and the ambient temperature;
2. We adopt a value of I_D and is replaced in Eq. (51) in which the other parameters are known. Thus is found the value I_c;
3. Using the values plotted in Fig. 3 takes the value of $f(I_c)$ and replaced in the Eq. (45) to find the value of $f(I_D)$;
4. From the curve of Fig. 3 takes the value of I_D;
5. Returns to the step 2 to converge the value of I_D.

In Tab. 2 the results of these iterations are presented.

Table 2. Results of iterations

Parameters	Iteration 1	Iteration 2	Iteration 3	Iteration 4
I_C	278.9	297.1	298.2	298.3
$f(I_C)$	2855	2796	2793	2792
I_D	700	747.2	750.2	750.4
$f(I_D)$	658.9	645.3	644.5	644.4

After the fourth iteration is observed that the DNI value that optimizes the LFR field in Natal/Brazil is 750.4 W/m^2. In addition, the model allows to compute the minimum required value IND function for the CLF the minimum conditions for the case study which corresponds to the value of 298.3 W/m^2.

4. CONCLUSIONS

This work is developed the mathematical model to calculate the optimal amount of DNI. From the values obtained by iterations is possible to make a sizing of the collector field that meets the climatic conditions where the system it shall be installed. Also, using the implemented methodology is possible to design various system configurations that use the CSP technology.

Although the analysis has been focused on the CSP technology facing RFL the methodology can also be used for the technologies CPC and CT.

It should be noted that the model implemented in this work is theoretical. However the developed model does not lose relevance due to good approximation that this model has with reality (Duffie and Beckman (2013) and Desai *et al.* (2014)).

5. REFERENCES

Canavarro, D., 2010. “Modeling field of linear fresnel solar collectors type; application to an innovative concentrator type lfsc”.

Desai, N.B., B., K.S. and S., B., 2014. “Optimization of design radiation for concentrating solar thermal power plants without storage”. *Solar Energy*, Vol. 107, pp. 98–112.

Duffie, J.A. and Beckman, W.A., 2013. *Solar Engineering of Thermal Processes*. John Wiley & Sons, New Jersey, 4th edition.

Fernandez-Garcia, A., Zarza, E., Valenzuela, L. and Perez, M., 2010. “Parabolic-trough solar collectors and their applications”. *Renew. Sustain. Energy Rev.*, Vol. 14, pp. 1695–1721.

Purohit, I., Purohit, P. and Shekhar, S., 2013. “Evaluating the potential of concentrating solar power generation in northwestern india”. *Energy Policy*, Vol. 62, pp. 157–175.

Stine, B.W. and Geyer, M., 2001. “Power from the sun”. 18 Jun. 2015 <http://www.powerfromthesun.net/>.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.