STUDY OF PARABOLOIDAL OPTICAL CONCENTRATOR BY RAY-TRACING METHOD: FOUNDATIONS

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Abstract

This paper presents a software tool, Ray-Tracer, which allows the simulation of a small size paraboloidal concentrator of non-imaging type. The software tool uses the ray-tracing method in order to simulate the propagation of the light and its reflection on a surface. We define all involved physical measures: optical concentration factor, maximum of the optical concentration factor, geometrical concentration factor, optical efficiency, and all equations based on which the measures characterizing the solar radiation can be computed. The simulations were conducted for the days corresponding to equinox and solstice moments. All these results are in agreement with results reported in literature illustrating the fact that the proposed software tool is competitive.

1. Introduction

In the competition between classically obtained electric energy and photovoltaically obtained electric energy, the solar generated energy price is prohibitive, because the materials are expensive and the efficiency is low. A solution consists in the concentration of solar light. In this way, the conversion efficiency can grow from 14% up to 30%. Though, the using of concentrators that follow the sun is not a realist solution because the installation price is high and inconvenient for users. As a consequence, there are used cheaper static concentrators that are also easy to use [1, 2, 3].

The paper presents a study on a paraboloidal concentrator with small dimensions using the Ray-Tracing method that follows the rays through the concentrator to the cell or until they have the system.

2. Theory

2.1. Paraboloidal concentrator

We can choose different shapes for the static concentrator useful surfaces. Using some software allowing the simulation of the light rays way is convenient. For this paper we chose a paraboloidal concentrator. The parabola equation is

$$y^2 = 2px, \tag{1}$$

where p is the parabola parameter. The focal distance is

$$f = p/2. \tag{2}$$

The rotation paraboloid equation is (Fig. 1)

$$x^2 + y^2 - 2a^2z = 0, \tag{3}$$

where a is the radius of the circle obtained by intersecting the paraboloid with the xOy plane at the distance $z=1$.

Figure 2 shows the generalized scheme of a concentrator: $A_{in}= A_{conc}$ is the area of the light input aperture, $A_{out}= A_{rec}$ is the area of the exit aperture, $\theta_{max, in}$ is the maximum incidence angle, on the entrance aperture, at which it produces the concentration, $\theta_{max, out}$ is the maximum angle at which the radiation falls on the receptor (PV cell). The maximum concentration optic factor is [2, 4, 5]

$$C_{\max} = \frac{n^2}{\sin^2(\theta_{\max,in})}, \tag{4}$$

where n is the refraction index of the environment in which the cell is immersed (for air $n=1$). For incidence angles between 0 and $\theta_{max, in}$, the optic concentration factor is equal to the ratio between the radiant flow density on the receiver, B_{rec}, and the radiant flow density on the input aperture, B_{conc}

$$C_{optic} = \frac{B_{rec}}{B_{conc}}. \tag{5}$$

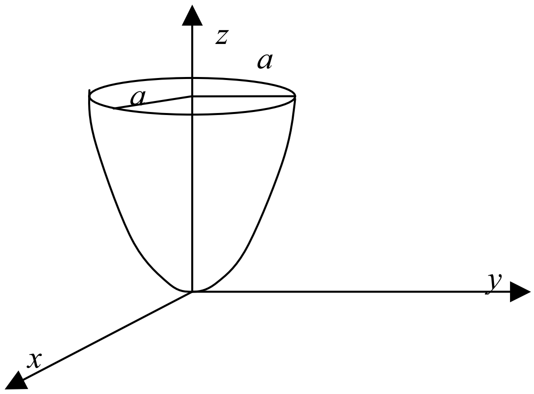

Fig. 1.

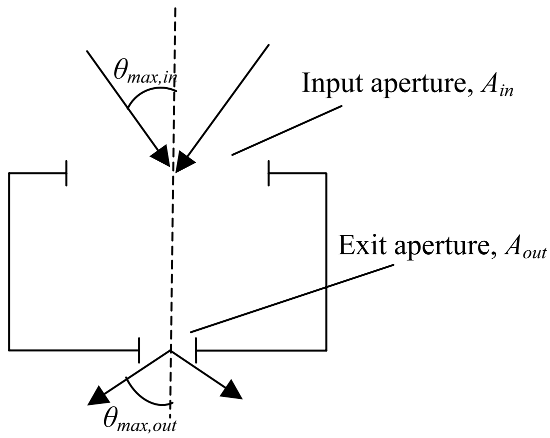

Fig. 2.

The geometric concentration factor is

$$C_{geom} = \frac{A_{in}}{A_{out}}. \tag{6}$$

The concentrator performances are determined by the optical efficiency, I_{optic}, which is defined as a proportion between the optic concentration factor and the geometric concentration factor

$$I_{optic} = \frac{C_{optic}}{C_{geom}}. \tag{7}$$

The optical efficiency varies between 0 and 1.

2.2. The solar radiant flow density

The Sun declination, δ, at the solar noon in a day of the year, n ($n = \overline{1,365}$), is calculated by the equation

$$\delta[rad] = \pi \frac{23,45}{180} \sin(2\pi \frac{284+n}{365}). \tag{8}$$

In equation (8), n is calculated with the equation [6, 7, 8]

$$n = 30.416(\ell - 1) + \chi , \tag{9}$$

where: ℓ is the month ($\ell = \overline{1,12}$) and χ is the number of the day of the month.

The hour angle ω is given by the equation

$$\omega = \frac{\pi}{12}(\tau_S - \tau_0), \tag{10}$$

where τ_S is the solar time (solar hour) and τ_0 is the solar noon, $\tau_0 = 12$.

The solar hour is defined as

$$\tau_S = \tau_L + E - 4(\varphi_L - \varphi_l). \tag{11}$$

In equation(11), φ_L is the legal longitude, φ_l is the place longitude, τ_L is the legal hour, and E is the time equation,

$$E = 2.292(0.0075 + 0.1868\cos\beta - 3.2077\sin\beta - 1.4615\cos 2\beta - 4.089\sin 2\beta), \tag{12}$$

where the angle β is

$$\beta[rad] = \frac{2\pi}{365}(n-1). \tag{13}$$

The incidence angle, θ, of the radiation on the surface inclined at the s angle, oriented at the azimutal angle γ is [9, 10, 11]

$$\begin{aligned}\cos\theta &= \sin\delta\sin\phi\cos s - \sin\delta\cos\phi\sin s\cos\gamma + \cos\delta\cos\phi\cos s\cos\omega + \\ &+ \cos\delta\sin\phi\sin s\cos\gamma\cos\omega + \cos\delta\sin s\sin\gamma\sin\omega \cdot\end{aligned}, \tag{14}$$

where ϕ is the latitude of the place.

For $s=0$, we obtain the zenithal distance θ_Z,

$$\cos\theta_z = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega. \tag{15}$$

At ground, the solar intensity, B, is

$$B = S(1 + 0.0034\cos n)a \cdot \exp(-d/\cos\theta_z). \tag{16}$$

where: S =1353 W/m^2, a = 0.88, d = 0.28.

On the surface, A, with random orientation, θ, the radiant flow density is

$$B_A = B\cos\theta . \tag{17}$$

If the radiation concentrated from the A_1 on the A_2, $A_2 << A_1$, the concentrated flow density is

$$B_{A2} = B_{A1} \cdot A_1 / A_2 . \tag{18}$$

3. The Ray-Tracer software

In this paper the Ray-Tracing method is used to describe the propagation of the light and the reflection on a surface [12, 13, 14, 15]. The Ray-Tracer software applying the Ray – Tracing method is used to study the paraboloidal concentrator. The concentrator is of non-imaging type. The small dimension paraboloidal concentrators are considered as architectural elements mounted on the house roofs. The paraboloid walls are made out of very cheap plastic materials covered with vacuum-deposited nanometric film made of aluminium or silver. The reflexion coefficient, R, does not depend on the incidence angle and we consider for R the value, R=0.96. The concentrated radiation is incident on the nanostructured photovoltaic cells located in the focal plan of the paraboloid. The efficiency of the photovoltaic cells increases from 14-16% up to 24 - 30% [16, 17, 18].

The software uses equations (1) –(3) to build the concentrator and equations (4) – (18) to calculate the radiant flow density on the input aperture and the optical concentration factor. We consider that the radiation that is incident on the phtovoltaic cell is fully absorbed by it. The radiant flow density on the output aperture, B_{rec}, is calculated by the equation

$$B_{rec} = \frac{N_{abs}}{N_{initial}} \left(\frac{R}{r} \right)^2 B_{conc} . \tag{19}$$

The meanings of the measures in equation (19) are: B_{conc} is the radiant flow density on the input aperture, R is the input aperture radius; r is the output aperture radius; $N_{initial}$ is the initial numbers of rays; N_{abs} is the number of rays on the output aperture considered to be absorbed of photovoltaic cell. The measures given by the user are: the input aperture radius, R (mm); the output aperture radius r(mm) considered to be equal to the receptive cell radius; the position of the receptive cell, H_0; the initial moment of the measures, τ_0; the final moment of the measurings, τ_l; the incrementation of the time $d\tau$; the inclination angle of the roof, s; the month of the year, l; the day of the month, χ.

The calculated and shown measures are: the intensity of the solar, B_n; the angle of incidence of the radiation on the input aperture, θ; the density of the radiant flow in the plane that contains the input aperture, B_{conc}; the density of the radiant flow in the plane that contains the photovoltaic cell B_{rec}; the optical concentration factor, C_{optic}; the quantity of energy that passes the input aperture during the measurements, Q_{conc}; the quantity of energy received by the cell, $Q_{rec} \equiv Q_{PV}$; the concentrator efficiency η, $\eta = Q_{PV} / Q_{conc}$.

The concentration is efficient if the optical concentration factor is bigger than 1. With the help of the tables or of the graphics we can determine the maximum angle of incidence θ_{max} and the time period for which $\theta \le \theta_{max}$.

Below we present an example with the calculus of the density of solar flow during the spring equinox. On the spring equinox, for the condition mentioned above, the incidence angle has the minimal values. At noon, in the limits given by the time equation, the angle of incidence can be null, $\theta \to 0$. As a consequence, during equinoxies the concentrator behaviour is optimum. Therefore, in the sequel the concentrator behaviour on the spring equinox is studied. Table 1 shows the orar variation of B_n (the solar radiant flow density), B_{conc}, B_{rec}, C_{optic}, Q_{conc}, Q_{rec} and η for the day of March 22, between 8 a.m. and 6 p.m.

Table 1. The density of the solar flow on March 22.

Time of day	θ[deg]	B_n [W/m^2]	B_{conc} [W/m^2]	B_{rec} [W/m^2]	C_{optic}	Q_{conc} [J]	Q_{PV} [J]	η [%]
8 a.m.	63.832	492.426	217.158	0.000	0.000	145768	36970	25.36
9 a.m.	48.834	655.369	431.391	56.943	0.132			
10 a.m.	33.835	740.468	615.061	522.284	0.849			
11 a.m.	18.836	784.194	742.194	1347.730	1.815			
noon	3.838	801.013	799.216	2835.097	3.547			
1 p.m.	11.160	795.701	780.653	2272.330	2.910			
2 p.m.	26.159	766.797	688.255	910.378	1.322			
3 p.m.	41.158	705.588	531.235	253.989	0.478			
4 p.m.	56.156	589.338	328.217	0.000	0.000			
5 p.m.	71.154	361.133	116.650	0.000	0.000			
6 p.m.	86.152	8.001	0.536	0.000	0.000			

The analysis of Table 1 shows the following aspects: at legal noon, the angle of incidence is 3.838 deg; between 8 a.m. and 4:30 p.m. the intensity of direct radiation is higher than 400 W/m^2; on the input aperture, the density of the radiant flow is higher than 400 W/m^2 between 9 a.m. and 3:30 p.m.; on the receptor, the density of the radiant flow is higher than 400 W/m^2 between 10 a.m. and 2:30 p.m.; the optic concentration factor is higher than 1 between 10:30 a.m. and 2:30 p.m.; the maximum of the optic concentration is 3.547; the efficiency of the concentrator is 25.36%.

Acknowledgements

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References

[1] M.R. Swanson, Section 11 - Photovoltaic concentrators in Handbook of Photovoltaic science and engineering, Edited by A. Luque and S. Hegedus, Publishing John Wiley and Sons Ltd, England, p. 475, 1138, 2002.
[2] B.E.S. Bowden, Ph. Thesis, University of New South Wales Sydney, NSW. Australia, April, p. 38, 131, (1996).
[3] M. Brogren, Ph. Thesis, Faculty of Sci. and Tech. Uppsala Univ., Sweden, p. 24, 160, (2004).
[4] K. Emery, Section 16 - Measurement and characterization of solar cells and modules in Photovoltaic science and engineering, Edited by A. Luque and S. Hegedus, Publishing John Wiley and Sons Ltd, England, p. 702, 1138, 2002.
[5] J. Nilsson, Licen. Thesis, Lund Univ., Faculty of Engin. LTH, Sweden, p. 32, 226, (2005).
[6] Al. Danescu, S. Bucurenciu, St. Petrescu, The utilization of solar energy, Editura Tehnica, Bucuresti, 336, 1982.
[7] L. Fara, E. Tulcan-Paulescu, M. Paulescu, Photovoltaic Systems, (in Romanian), Editura Matrix Rom, Bucuresti, 145, 2005.
[8] M. Paulescu, Z. Schlett, Practical aspects in the photovoltaic conversion of the solar energy, (in Romanian), Editura Mirton, Timisoara, 114, 2002.
[9] C. De Sabata, I. Luminosu, A. De Sabata, A. Palea, Scientific Bulletin of the "Politehnica" of Timisoara, Transactions of Mechanics, 52(66)4, 82, (2007).
[10] I. Luminosu, C. De Sabata, A. De Sabata, Bult. AGIR, Bucuresti, XII, 3, Jul–Sep., 31, (2007).
[11] M. Paulescu, Algoritms for estimating the values of the solar energy, (in Romanian), Editura Matrix Rom, Bucuresti, 105, 2005.
[12] R. Winston, Solar Energy, 16(5), 89, (1974).
[13] R.K. McIntosh, M.R. Swanson, E.J. Cotter, Progress in Photovoltaics: Research and Applications, 14(2), 167, (2006).
[14] L.J. Gray, Section 3 - The physics of the solar cell in Photovoltaic science and engineering, Ed. by A. Luque and S. Hegedus, Publ. John Wiley and Sons Ltd, England, p. 106, 1138, 2002.
[15] A. Glassner, An introduction to ray tracing, Publisher: Morgan Kaufmann, Academic Press, San-Diego, 327, 1989.
[16] I. Luminosu, I. Zaharie, M. Costache, I. Damian, Proceedings of the National Conference for Installations in Civil Engineering and Ambient Comfort, (in Romanian), "Politehnica" University of Timisoara, 183, (2007).
[17] I. Luminosu, I. Zaharie, M. Costache, I. Damian, Proc. of the Nat. Conf. for Install-s in Civil Eng. and Ambient Comfort, (in Romanian), "Politehnica" Univ. of Timisoara, 191, (2007).
[18] I. Luminosu, M. Nagy, Bulletins for Applied and Computer Mathematics, Budapest, University of Technology and Economics, BAM, 2173, 135, (2004).