Calculation of the Radiant Flux Density Distribution in the Focal Plane of Parabolocylindrical Mirror-Concentrating Systems

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ABSTRACT

This work considers analytical approaches for calculating the density distribution of radiant fluxes from the Sun for a parabolic-cylindrical Mirror-Concentrating System (MCS).

KEYWORDS: *mirror-concentrating systems, degree of concentration, focus, optical-energy parameters, parabolic cylinder, concentrator*

As you know, the structure of the scattering spot from a separate zone of the reflecting surface of the MCS (often used in solar engineering of a paraboloid, a parabolic cylinder, and also a Fresnel mirror-concentrating system) is analyzed on the basis of a model for calculating the distribution of the radiant flux density from various radiation sources (the Sun, imitating emitters) on the plane of the receiving surface receiver of the MCS converter [1-7]. In this case, the main provisions are as follows.

- the infinitesimal element of the mirror-concentrating system reflects without expanding, the elementary image (EI) of the radiation source (apparent angular size is $2\gamma_0$), i.e. the nature of the distribution of the density of the radiant flux on the surface of the emitter remains unchanged (for example, for a radiation source the Sun is taken as a blackbody in the form of an equally emitting sphere with a surface heating temperature of 5800 ^{0}K or in the form of an empirical dependence of Jose [8]).
- in view of the constructive and technological inaccuracy in the manufacture of the reflecting surface, the density of the radiant flux coming from the radiation source, after specular reflection with the coefficient R_3 of the elementary sections of the zone, decreases depending on the degree of inaccuracy $\Delta\alpha \approx 4\sigma_{cp}$, where σ_{cp} - is the spatial average value of the measured angular deviations of the normals of the RS MCS from their theoretical directions [9-16];
- the density of the radiant flux of the radiation source E_c arriving at the RS MCS after reflection with the coefficient R_3 from its elementary dS central circular zone decreases without changing its structure, due to the averaged inaccuracy $\Delta\alpha \approx 4\sigma_{cp}$, these are the density ΔE_{r0} on the plane of the ray-receiving surface of the transducer receiver.

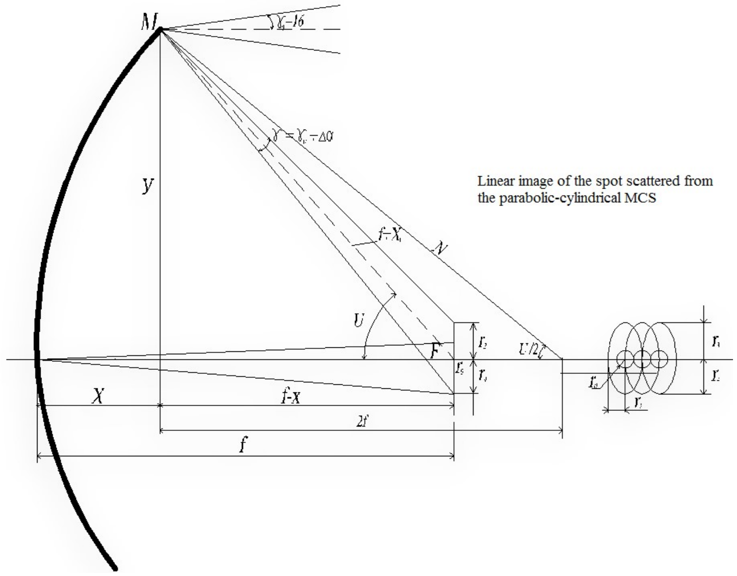

Figure-1. Formation of a scattering spot of a linear focal plane for a parabolic-cylindrical MCS.

For parabolic cylindrical MCS: $$\Delta E_{r0} = R_3 E_c \left(\frac{r_0}{r_\sigma} \right). \quad (1)$$

For the RS of a parabolic MCS and a solar radiation source in the focal plane of the ray-receiving surface (1) is specified (see Figure-1)

$$r_0 = ftg\gamma_0; \qquad r_\sigma = ftg(\gamma_0 + \Delta\alpha); \quad (2)$$

here R_3 - is the integral coefficient of specular reflection of the solar radiant flux; γ_0 - half of the apparent angle of the Sun (for the Earth's orbit γ_0=16′), $\gamma = \gamma_0 + \Delta\alpha$ - the average angle of increase of reflected radiant fluxes from the RS of real systems of specular reflection.

Then $$\Delta E_{r0} = R_3 E_c \frac{tg\gamma}{tg^2\gamma} = R_3 E_c \frac{tg\gamma}{tg^2(\gamma_0 + \Delta\alpha)}. \quad (3)$$

ΔE_r - the density of the radiant flux of the radiation source arriving on the plane, of the ray-receiving surface of the receiver from other elementary sections of the annular zones of the reflecting surface of the MCS of the paraboloid or linear zones for the parabolic cylinder, also changes depending on the area of the EI trace on the surface of the receiver, i.e. expressions for the density of the radiant flux at the considered point r_σ - the receiving surface of the MCS receiver from the elementary section of the annular zone of the linear zone $dS_{пц}$ -parabolic cylinder have the form

$$\Delta E_{ri_{пц}} = R_3 E_c \left(\frac{r_0}{r_{4i}} \right). \quad (4)$$

For a parabolic-cylindrical MCS in the focal plane r_{4i} [10], where r_{4i} - is the large semiaxis of the trace of the ellipse from the elementary display of the EO in the focal plane of the MCS [17-20].

U_i - the theoretical value of the angle of deflection of the beam arriving at the focus from the considered extreme point Mi of the elementary section of the mirror-concentrating surface relative to the optical axis of the MCS.

Therefore, for a parabolic cylinder

$$\Delta E_{ri} = R_3 E_c \frac{\left(1 - tg^2 \frac{U_i}{2} - 2tg \frac{U_i}{2}\right) tg\gamma}{\left(1 + tg^2 \frac{U_i}{2}\right)^2 tg\gamma} . \qquad (5)$$

From the elementary straight zone of the RS MCS of the parabolic cylinder dy_i with radius y_i to the point r_i in the focal zone, the density, compacted in the sogital and meridional directions, falls equal to:

$$dE_{ri} = R_3 E_c \left(\frac{r_0}{r_i}\right) \frac{y_i}{r_{4i}} dy_i . \qquad (6)$$

For parabolic cylinder $y_i = 2ftg\frac{U_i}{2}$ is opening angle U_i is selected depending on r_i from relations (1),(4),(5). From here

$$dE_{ri} = 4fR_3 E_c \left(\frac{r_0}{r_{4i}}\right) \left(\frac{2tg\frac{U_i}{2}}{r_{4i}}\right) d\left(tg\frac{U_i}{2}\right) . \qquad (7)$$

E_{ri} - the total density of the radiant flux at point r_i - taking into account the formation zones of this flux is equal to the sum of certain integrals

$$\int_{E_{ri}}^{E_{im}} dE_i = \int_{y_{4i}}^{y_{r4m}} R_3 E_c \left(\frac{r_0}{r_{4i}}\right)\left(\frac{y_i}{\pi r_i^2}\right) dy_i + \int_{y_{3i}}^{y_{3im}} R_3 E_c \left(\frac{r_0}{r_{3i}}\right) \frac{y_i}{\pi r_i^2} dy_i + \int_{y2i}^{y_{2im}} R_3 E_c \left(\frac{r_0}{r_{2i}}\right) \frac{y_i}{\pi r_i^2} dy_i \qquad (8)$$

For parabolic cylindrical RS MCS $E_{rm} = R_3 E_c \left(\frac{r_0}{r_i}\right)$; $y_{ri} = 2tg\frac{U_{4i}}{2}$; $y_{r3i} = 2ftg\frac{U_{3i}}{2}$;

$y = ftg\frac{U_{2m}}{2}$; $y_{rm} = 2ftg\frac{U_{4m}}{2}$; $y_{r3m} = 2ftg\frac{U_{3m}}{2}$; $y_{r2m} = 2ftg\frac{U_{2m}}{2}$;

U_{4m} - maximum aperture angle. Since E_c, R_3, r_0 and U do not depend on dy_i, we obtain

$$E_{ri} - E_{rm} = 2R_3 E_c \left(\frac{r_0}{r_{4i}}\right)\left[\int_{y_{r4i}}^{y_{r4m}} \frac{y_i}{r_{4i}} dy_i + \int_{y_{r3i}}^{y_{r3m}} \frac{y_i}{r_{3i}} dy_i + \int_{y_{r2i}}^{y_{r2m}} \frac{y_i}{r_{2i}} dy_i\right], \qquad (9)$$

where $E_{rm} = R_3 E_c \left(\frac{r_0}{r_{4m}}\right)^2$; $r_{4m} = f\frac{\left(1 + tg^2\frac{U_m}{2}\right)^2 tg^2\gamma}{1 - tg^2\frac{U_m}{2} - 2tg\frac{U_m}{2} tg\gamma}$; $r_{3i} = f\frac{\left(1 + tg^2\frac{U_i}{2}\right)^2 tg\gamma}{1 - tg^2\frac{U_i}{2} + 2tg\frac{U_i}{2} tg\gamma}$;

$r_{2i} = f\left(1 + tg^2\frac{U_i}{2}\right) tg\gamma$.

Lower and upper redistributions

$$\left.\begin{aligned} r_i &= f\frac{\left(1+tg^2\frac{U_{4m}}{2}\right)^2 tg\gamma}{1-tg^2\frac{U_{4i}}{2}-2tg\frac{U_{4i}}{2}tg\gamma}, \\ r_i &= f\frac{\left(1+tg^2\frac{U_{3i}}{2}\right)^2 tg\gamma}{1-tg^2\frac{U_{3i}}{2}+2tg\frac{U_{3i}}{2}tg\gamma}, \\ r_i &= f\left(1+tg^2\frac{U_{2i}}{2}\right)^2 tg\gamma \quad \text{or} \quad \mathrm{tg}\,\frac{U_{2i}}{2}=\sqrt{\frac{r_i}{ftg\gamma}-1} \end{aligned}\right\}. \tag{10}$$

Supplying all the initial data, we determine the integrals of the types

$$C_{r4}=2R_3E_c\left(\frac{tg\,\gamma}{tg^2\gamma}\right)\left(\frac{f}{r_i}\right)\int_{tg\frac{U_{4i}}{2}}^{tg\frac{U_{4m}}{2}}\frac{\left(1-tg^2\frac{U_i}{2}-2tg\frac{U_i}{2}tg\,\gamma\right)tg\frac{U_i}{2}}{\left(1+tg^2\frac{U_i}{2}\right)^4}d\left(tg\frac{U_i}{2}\right); \tag{11}$$

$$C_{r3}=2R_3E_c\left(\frac{f}{r_i}\right)\left(\frac{tg\,\gamma}{tg^2\gamma}\right)\int_{tg\frac{U_{3i}}{2}}^{tg\frac{U_{3m}}{2}}\frac{\left(1-tg^2\frac{U_i}{2}-2tg\frac{U_i}{2}tg\,\gamma\right)tg\frac{U_i}{2}}{\left(1+tg^2\frac{U_i}{2}\right)}; \tag{12}$$

$$C_{r2}=2R_3E_c\left(\frac{tg\,\gamma}{tg^2\gamma}\right)\left(\frac{f}{r_i}\right)\int_{tg\frac{U_{ri}}{2}}^{tg\frac{U_{2m}}{2}}\frac{tg\frac{U_i}{2}}{\left(1+tg^2\frac{U_i}{2}\right)^2}d\left(tg\frac{U_i}{2}\right). \tag{13}$$

In relative terms, by replacing the integrands, we have

$$\overline{C}_{r4}=\frac{C_{r4}}{R_3E_c};\ \overline{C}_{r3}=\frac{C_{r3}}{R_3E_c};\ \overline{C}_{r2}=\frac{C_{r2}}{R_3E_c};\ \overline{C}_{r2}=\frac{C_{r2}}{R_3E_c}\frac{f}{r_i}=\frac{1}{r_i};$$

$$\frac{x_{4i}}{x_{4im}}=x_4;\ \frac{x_{3i}}{x_{3im}}=x_3;\ \frac{x_{2i}}{x_{2im}}=x_2;\ tg\frac{U_i}{2}=x;$$

$$\overline{C}_{r4}=\frac{tg\,\gamma}{tg^2\gamma}\frac{1}{r_i}\int_{x_4}^{1}\frac{\left(1-x^2+2xtg\,\gamma\right)x}{\left(1+x^2\right)^4}dx; \tag{14}$$

$$\overline{C}_{r3}=\frac{tg\,\gamma}{tg^2\gamma}\frac{1}{r_i}\int_{x_3}^{1}\frac{\left(1-x^2+2xtg\,\gamma\right)x}{\left(1+x^2\right)^4}dx; \tag{15}$$

$$\overline{C}_{r2}=2\frac{tg\,\gamma}{tg^2\gamma}\frac{1}{r_i}\int_{x_2}^{1}\frac{x}{\left(1+x^2\right)^2}dx. \tag{16}$$

The solution of these integrals gives the following:

$$\int_{x_4}^{1}\frac{\left(1-x^2+2xtg\gamma\right)x}{\left(1+x^2\right)^2}dx=\frac{1}{2}\left\{\frac{4}{3\left(1+\overline{x}_4^2\right)^3}-\frac{2}{\left(1+\overline{x}_4^2\right)^2}-\frac{1}{1+\overline{x}_4^2}-\frac{1}{6}-2tg\gamma\left[\frac{1}{3\left(1+\overline{x}_4^2\right)^3}-\frac{1}{2\left(1+\overline{x}_4^2\right)^2}+\frac{1}{12}\right]+\right.$$

$$\left.+2tg^2\gamma\left[\frac{1}{2\left(1+\overline{x}_4^2\right)^2}-\frac{1}{3\left(1+\overline{x}_4^2\right)^3}-\frac{1}{12}\right]\right\}, \qquad (17)$$

$$\int_{x_3}^{1}\frac{\left(1-x^2+2xtg\gamma\right)x}{\left(1+x^2\right)^4}dx=\frac{1}{2}\left\{\frac{4}{3\left(1+\overline{x}_3^2\right)^3}-\frac{2}{\left(1+\overline{x}_3^2\right)^2}-\frac{1}{1+\overline{x}_3^2}-\frac{1}{6}-2tg\gamma\left[\frac{1}{3\left(1+\overline{x}_3^2\right)^3}-\frac{1}{2\left(1+\overline{x}_3^2\right)^2}+\frac{1}{12}\right]+\right.$$

$$\left.+2tg^2\gamma\left[\frac{1}{2\left(1+\overline{x}_3^2\right)^2}-\frac{1}{3\left(1+\overline{x}_3^2\right)^3}-\frac{1}{12}\right]\right\}, \qquad (18)$$

$$\int_{x_2}^{1}\frac{x}{\left(1+\overline{x}^2\right)^2}dx=\frac{1}{2}\left(\frac{1}{1+\overline{x}_2^2}-\frac{1}{4}\right). \qquad (19)$$

Based on the results obtained, taking into account the conditions of visibility of the RS MCS zones from the point r_i, an analytical [21-30] expression for the distribution of energy (radiant flux density) in the focal plane for a parabolic-cylindrical MCS, taking into account the manufacturing accuracy (σ), the mirror aperture (U_i) and angular dimensions ($2\gamma_0$) and the energy density E_c from the radiation source

$$E_{ri}=R_3E_c\frac{tg\gamma}{tg^2\gamma}\left[\left(\frac{f}{r_i}\right)\overline{C}_r+\frac{\left(1-tg^2\frac{U_i}{2}-2tg\left(\frac{U_i}{2}\right)tg\gamma\right)^2}{\left(1+tg^2\frac{U_i}{2}\right)^2}\right], \qquad (20)$$

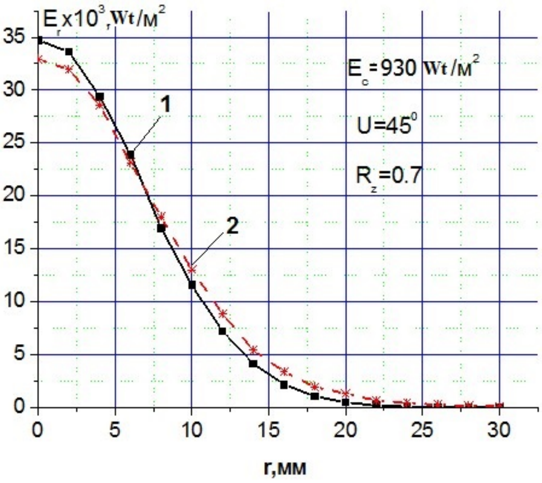

Figure-2. Calculated and experimental curves of the energy density distribution of the concentrated radiant flux of the Sun in the focal plane: 1 - calculated curve; 2 - experimental curve.

where: $$\overline{C}_r=N\left[\left\{\frac{4}{3\left(1+\overline{x}_4^2\right)^3}-\frac{2}{\left(1+\overline{x}_4^2\right)}+\frac{1}{1+\overline{x}_4^2}-\frac{1}{6}\right]-4tg\gamma\left[\frac{1}{3\left(1+\overline{x}_4^2\right)^3}-\frac{1}{2\left(1+\overline{x}_3^2\right)^2}-\frac{1}{12}\right]+$$

$$+ 2tg^2\gamma\left[\frac{1}{2\left(1+\bar{x}_4^2\right)^2} - \frac{1}{3\left(1+\bar{x}_4^2\right)^2} - \frac{1}{12}\right]\Bigg\}; \qquad (21)$$

N=3 for $tg\gamma < \bar{r}_i \le 2tg\gamma$; N=2 for $2tg\gamma < \bar{r}_i \le \bar{r}_{3m}$; N=1 for $\bar{r}_{3m} < \bar{r}_i \le \bar{r}_{4m}$; $x_4 = \frac{x_{4i}}{x_{4m}} = \frac{tg\frac{U_{4i}}{2}}{tg\frac{U_{4m}}{2}}$;

$$r_4 = \frac{r_{4i}}{f} = \frac{\left(1 + tg^2\frac{U_{4i}}{2}\right)^2 tg\,\gamma}{1 - tg^2\frac{U_{4i}}{2} - 2tg\frac{U_{4i}}{2}tg\,\gamma}; \quad r_{4m} = \frac{r_{4m}}{f} = \frac{\left(1 + tg^2\frac{U_{4m}}{2}\right)^2 tg\,\gamma}{1 - tg^2\frac{U_{4m}}{2} - 2tg\frac{U_{4m}}{2}tg\,\gamma}.$$

The previously proposed provisions of the computational model are applicable not only to the parabolic-cylindrical shape, but also to other types of MCS. This is shown by the example of calculating the distribution of the density of the radiant flux in the focal plane of the parabolic cylindrical shape of the MCS.

Thus, on the basis of the above approaches, an analytical expression (20) was derived for calculating the density distribution of the radiant flux from the Sun in the focal plane of the parabolic-cylindrical MCS.

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