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FLUX DISTRIBUTION AND INTERCEPT FACTORS IN THE FOCAL REGION OF A FACETED PARABOLOIDAL DISH CONCENTRATOR

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ABSTRACT

Illumination of the full moon has been adapted for photographic determination of spatial distribution of energy in the focal region of a faceted paraboloidal dish concentrator. The observed flux distribution is shown to be represented by the composition of two Gaussian distributions whose peaks coincide in the focal plane and are displaced apart in other parallel planes. The expression for the intercept factor as a function of aperture size is derived. Sample computational results are presented. The procedure outlined is particularly important in design of receivers/absorbers for point focussing systems whose optical characteristics and manufacturing tolerances are difficult to be modelled mathematically.

INTRODUCTION

Parabolic dish solar collector systems have received steadily increasing attention during this decade as a viable means for high temperature heat production for electricity generation and industrial processes. Such systems consist of two-axis sun-tracking dish concentrators with a receiver (usually a cavity-receiver) mounted at their focus. Evaluation of their optical/thermal performance requires knowledge of the energy flux distribution in the focal plane and an expression of the intercept factor as a function of receiver aperture size. Over the years many theories have been advanced to assess the flux distribution in the focal plane (See for example Wen et al (1980) for a review). In general, realistic optical systems are very complex and statistical in nature. Approximations and assumptions are, therefore, inevitably made for mathematical manageability. An approximation often used in this connection was devised by Duff and Lameiro (1974) and it assumes the flux distribution and related variables in the focal plane as of Gaussian distribution.

In recent years the use of surface receivers and modified cavity receivers has been suggested for application in low cost dishes of short focal length and rather imperfect optics (Schmidt et al (1983), Kaneff (1983)). Evaluation of systems with these receivers requires knowledge of flux distributions and intercept factors in the whole focal region and not just in the focal plane. Theoretically, such a determination is cumbersome and does not account for the factors resulting from manufacturing tolerances. In the following, we present a procedure and results of a relatively simple method for the determination of flux distribution and intercept factors in the focal region of a dish concentrator.

EXPERIMENTAL DETERMINATION OF FLUX DISTRIBUTION

A suitable experimental procedure (Thomas and Whelan (1981)) is similar to that of Hisada et al (1957) used for solar furnace measurements. It is based on the fact that the apparent diameter (diameter/distance from earth) of the moon is about 31.1', almost equal to the sun's (whose intense radiations would produce very high temperatures in the focal region). Illumination by the moon may therefore be adapted for the determination of flux distribution in the focal region. The determination, however, embraces an assumption that the surface brightness of the moon is proportional to that of the sun.

Measurements are made on the night of full moon. In the present example, the paraboloidal dish collector is 5m diameter, 19.8m² aperture area and 1.808m focal length (Kaneff, 1983). The dish shell is of 6mm thick fibreglass, has a rim angle of 70° and is rim supported. The reflector is formed by shaped 100mm x 100mm plane glass mirror segments. The dishes are integrated in a steel frame modular unit employing altitude and azimuth tracking driven by a control unit normally acting in response to sun sensor signals. For the measurements, a translucent mylar sheet (thickness = .006cm) was placed in the focal plane where the moon's image was photographed with a calibrated camera using various exposure times. The brightness of the moon's image at the periphery of each pattern is assumed proportional to the reciprocal of the exposure time. This yielded contours of constant brightness. Fig. 1 depicts such contours. Similar measurements were made in other planes parallel to the focal plane but at different axial distances from it. The relative intensity variations obtained from these measurements are shown in Fig. 2.

INTERCEPT FACTOR: FORMULATIONS

From the experimental measurements plotted in Fig. 2, it is apparent that the focal flux distribution may be represented by a composition of two Gaussian distributions. In a plane parallel to the focal plane (x-z plane) and at a distance y_o we have:

$$I(x,y_o) = \frac{I_o'}{2}\, e^{-c_1 y_o^2}\left[e^{-k(x+c_2y_o)^2} + e^{-k(x\ c_2y_o)^2}\right] \qquad (1)$$

where I_o', k, c_1 and c_2 are constants obtainable from the experimental curves.

$$I(x,y_o) = \frac{I_o}{2}\left[e^{-k(x+c)^2} + e^{-k(x-c)^2}\right] \qquad (2)$$

where $I_o = I_o'\, e^{-c_1 y_o^2}$ and $c = c_2 y_o$.

If dE is the energy received between circles of radii x and x + dx in the plane parallel to the focal plane and distant y_o from it, then

$$dE = 2\pi x dx I(x,y_o) = \frac{I_o}{2}\left[2\pi x e^{-k(x+c)^2}dx + 2\pi x e^{-k(x-c)^2}dx\right]$$

Put $x = \sqrt{A/\pi}$ or $\pi x^2 = A$

or $2\pi x dx = dA$

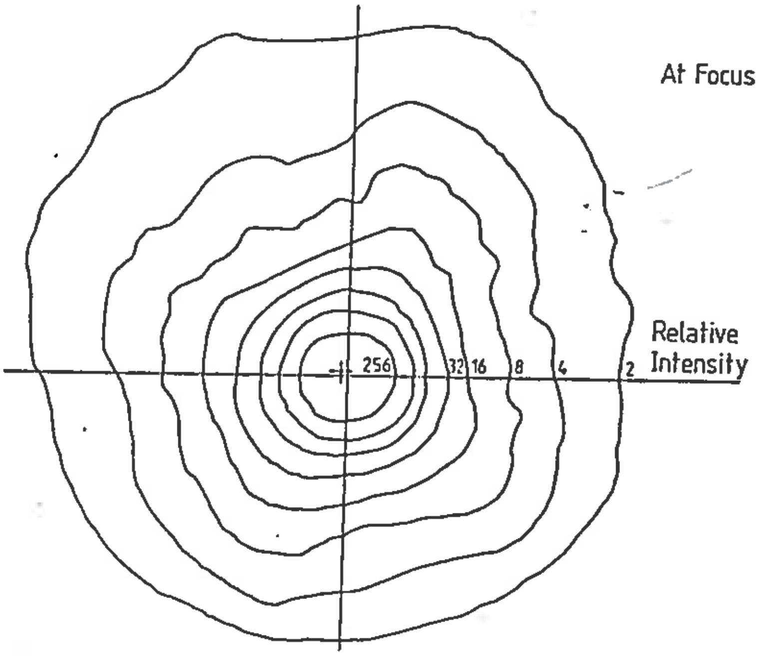
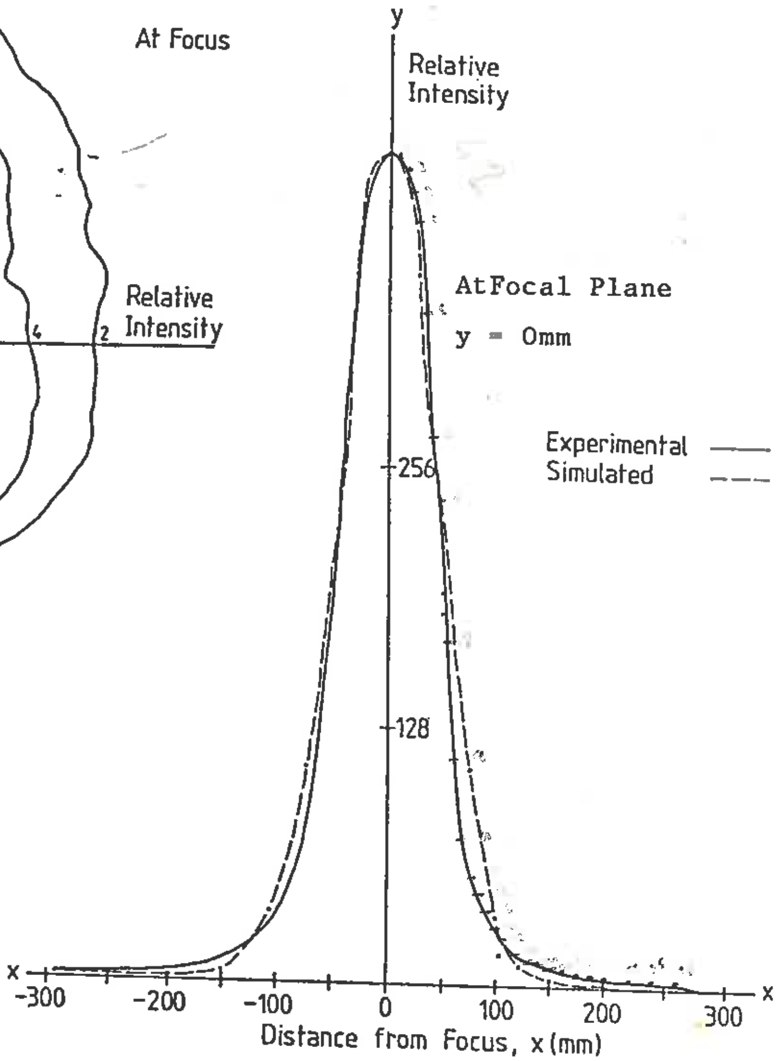


Fig. 1: Constant Brightness Contours on Focal Region Target



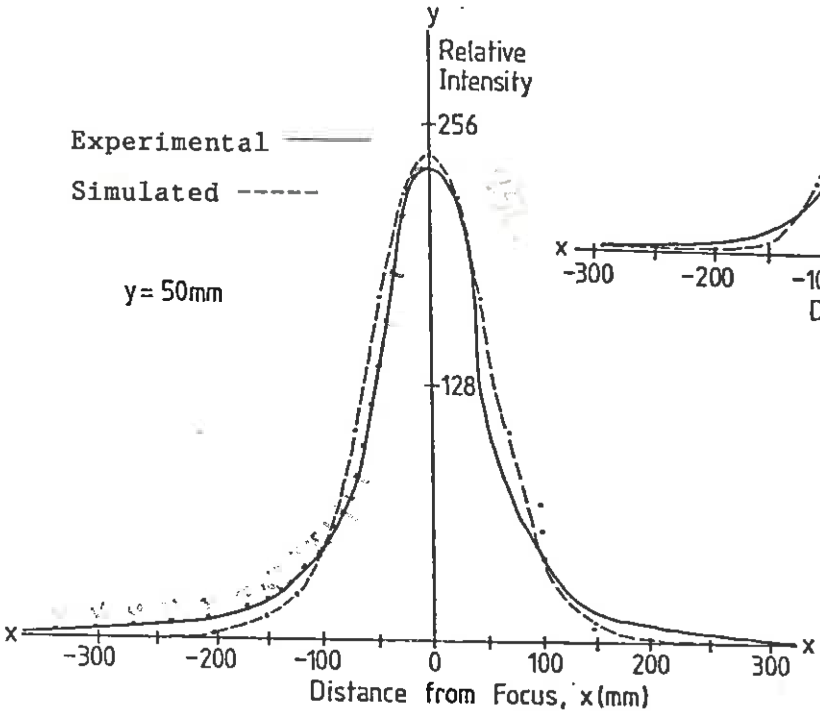
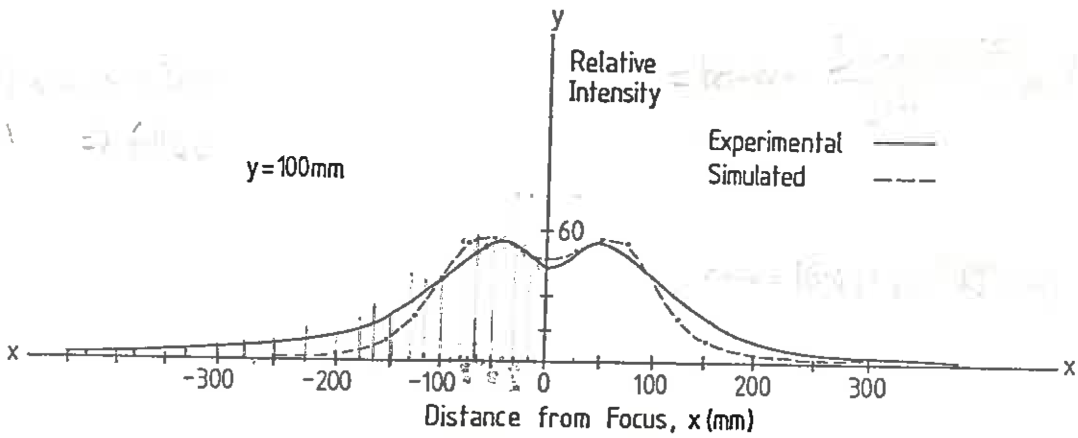


Fig. 2: Relative Intensity on Three Different Focal Region Planes



$$dE = \frac{I_o}{2} [e^{-k(\sqrt{A/\pi} - c)^2} dA + e^{-k(\sqrt{A/\pi} - c)^2} dA] \tag{3}$$

Intercept factor is defined as

$$\phi(x_o,y_o) = \frac{\int_0^{A_o} dE}{\int_0^{\infty} dE(y_o=0)} = \frac{E_o}{E_{to}} \tag{4}$$

where $A_o = 2\pi x_o$

and $E_o = \frac{I_o}{2} [\int_0^{A_o} e^{-k(\sqrt{A/\pi} + c)^2} dA + \int_0^{A_o} e^{-k(\sqrt{A/\pi} - c)^2} dA]$

Substituting $\sqrt{A/\pi} + c = y$ and $\sqrt{A/\pi} - c = z$ we have

$$E_o = \frac{\pi I'_o}{2k} [\int_c^{c+\sqrt{A_o/\pi}} e^{-ky^2} y\,dy - c \int_c^{c+\sqrt{A_o/\pi}} e^{-ky^2} dy$$

$$+ \int_c^{-c+\sqrt{A_o/\pi}} e^{-kz^2} z\,dz + c \int_{-c}^{-c+\sqrt{A_o/\pi}} d^{-kz^2} dz]$$

$$\text{or } E_o = \frac{\pi I_o}{2k} [2e^{-kc^2} - e^{-k(x_o+c)^2} - e^{-k(x_o-c)^2} + 2kcD_o] \tag{5}$$

$$\text{where } D_o = \int_{-c}^{-c+x_o} e^{-kz^2} dz - \int_c^{c+x_o} e^{-ky^2} dy \tag{6}$$

$$D_o = \frac{1}{\sqrt{k}} \cdot \frac{\sqrt{\pi}}{2} \{2\phi(c\sqrt{k}) - \phi[(c-x_o)\sqrt{k}] - \phi[(c+x_o)\sqrt{k}]\} \tag{7}$$

Also $E_\infty = \int_0^\infty dE(x_o,o) = \int_0^\infty I_o e^{-kx^2} 2\pi x\,dx = \frac{\pi I_o}{k}$

$$\phi_o(x_o,y_o) = \tfrac{1}{2} e^{-c\, y_o^2} [2e^{-kc^2} - e^{-k(x_o+c)^2} - e^{-k(x_o-c)^2} + 2kcD_o] \tag{8}$$

where D_o is given by (7)

RESULTS OF COMPUTATIONS

The assumed expression of focal flux distribution given by equation (1), could be fitted into the observed variations as shown in Fig. 2. The values of corresponding parameters are as follows.

I_o = 212
k = .00024 $(mm)^{-2}$
c = .000125 $(mm)^{-2}$
c_2 = .60

Using these parameters and equations (7) and (8), $\phi_o(x_o,y_o)$ was calculated for different values of x_o and y_o. The results are illustrated in Fig. 3.

DISCUSSION

For a dish concentrator, focal flux distribution information is usually required for design of the receiver/absorber. One approach is to perform slope error measurements with optical or contact probe methods (eg. Grilikhes (1968) and Krasilovskii and co-workers (1978)) and to obtain slope error statistics which may be used to compute focal flux distribution by numerical methods which are generally expensive. An alternative approach is to adopt the method outlined in the present paper, which seems easier and more meaningful.

In physical terms, representation of flux distribution by the composition of two Gaussian functions seems logical. Petit (1977) used the sum of two normal distributions to describe the angular distribution of light reflected from a metal or polymeric mirror. In the present case, reflection

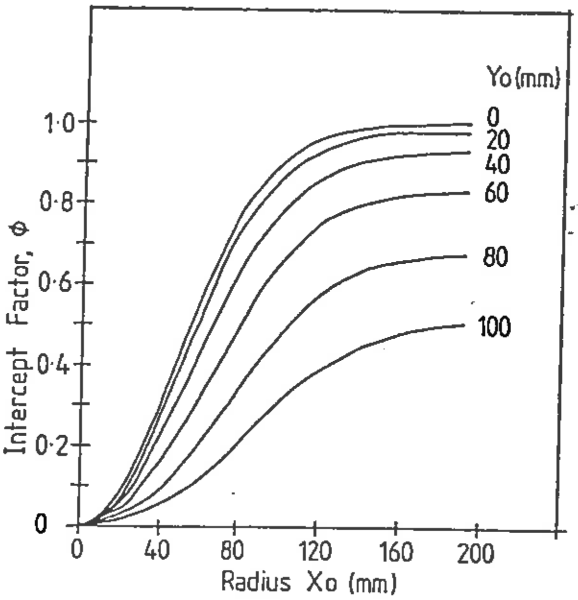


Fig. 3: Intercept factor vs. Radius

is from flat glass mirror segments and the reflected beam profile can be adequately represented by a Gaussian distribution. However, according to the concept of cone optics, the solar radiation reflected from each element of a dish would be a cone of rays which would cast an elliptical image on the focal plane. The flux mapping due to each hemisphere of dish would be the superposition of numerous elliptical images of various orientations and sizes. The mapping due to the other half of the dish would be identical and would overlap the first, in the focal plane. In other parallel planes the two component mappings would be displaced from each other.

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