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HOW TO MEASURE THE OPTICAL QUALITY OF FOCUSSING SOLAR COLLECTORS WITHOUT LASER RAY TRACING

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ABSTRACT

Designers and manufacturers need a tool for evaluating the optical quality of solar concentrators. In addition to the optical efficiency η_o, it is important to have a measure of optical errors and of losses due to reflected radiation missing the receiver. This paper describes a novel alternative to the laser ray trace technique. The new method does not require any equipment beyond what is used for measuring collector efficiency; it could therefore become part of routine collector testing. The total optical errors resulting from imperfect specularity and from inaccuracies in reflector position or slope are characterized by an angular standard deviation $\sigma_{optical}$, the rms deviation of the reflected rays from the design direction. The method is based on the fact that the off-axis performance of a concentrator depends on $\sigma_{optical}$. An angular scan is performed; i.e., the collector output is measured as a function of misalignment angle over the entire range of angles for which there is measurable output (typically a few degrees). This test should be carried out on a very clear day, with receiver close to ambient temperature (if the latter condition cannot be satisfied, appropriate corrections are necessary). The parameter $\sigma_{optical}$ is then determined by a least squares fit between the measured and the calculated angular scan. We tested the method on a parabolic trough collector manufactured by Hexcel but it is suitable for parabolic dishes as well. The method appears to be accurate enough to determine $\sigma_{optical}$ within about 10%.

1. INTRODUCTION

Evaluation of the optical quality of a solar concentrator is important: to the designer to tell him whether a collector needs improvement, and to the manufacturer to ensure proper quality control. The methods that are available or have been proposed for measuring the contour accuracy of solar concentrators require either laser ray tracing or flux mapping at the receiver surface. Both approaches provide very accurate results but are costly: the equipment is specialized and expensive and demands a good deal of time and/or expertise (1,2).

The question arises, therefore, whether the instantaneous efficiency measurements that are performed as part of a standardized performance evaluation (3) could somehow be used to determine $\sigma_{optical}$, the rms angular beam spread caused by optical imperfections. This paper shows that this can indeed be accomplished by misaligning the collector slightly away from the sun and measuring the efficiency for several values of the misalignment angle. The optical error $\sigma_{optical}$ is then extracted by finding the theoretical curve which best fits these misalignment data. Thus, the determination of $\sigma_{optical}$ could become part of the standard test procedures for concentrating solar collectors. The method is suitable for both photovoltaic and thermal collectors.

The theory underlying this technique is described in Section 2. Section 3 presents the test results for a parabolic trough collector with cylindrical receiver, manufactured by Hexcel. The data obtained with this collector indicates that the accuracy of this method is acceptable (on the order of ±10%).

2. THEORY

Since the theory of focussing solar collectors has been described elsewhere (4,5), a brief summary suffices at this point, and for simplicity we consider the line focus case. The crucial concepts are the angular acceptance function and the intercept factor. The angular acceptance function $f(\theta_\perp)$ is defined as that fraction of a uniform beam of parallel rays incident on the aperture at an angle $\theta_\perp$ from the optical axis that reach the receiver if the optics are perfect. For the example of a parabolic trough with cylindrical receiver, $f(\theta_\perp)$ is given by

$$f(\theta_\perp) = \begin{cases} 1 & \text{for } |\theta_\perp| < \theta_{\perp 1} \\ \cot\frac{\phi}{2}\left(\frac{2\tan(\phi/2)}{\pi C\theta_\perp} - 1\right)^{1/2} & \text{for } \theta_{\perp 1} < |\theta_\perp| < \theta_{\perp 2} \\ 0 & \text{for } |\theta_\perp| > \theta_{\perp 2}. \end{cases} \qquad [2\text{-}1]$$

where

$$\theta_{\perp 1} = \frac{\sin\phi}{\pi C}$$

$$\theta_{\perp 2} = \frac{2\tan(\phi/2)}{\pi C}$$

ϕ = rim angle, and

C = geometric concentration ratio.

The intercept factor $\gamma(\theta_m)$ is that fraction of rays from the sun that reach the receiver of a collector with real optical errors when the optical axis is misaligned by an angle θ_m from the center of the sun. The intercept factor is the convolution of the normalized angular distribution of the sun, the distribution of optical errors, and the angular acceptance function for perfect optics. The order of carrying out the convolution is immaterial; hence the problem can be treated as an equivalent source (defined as convolution of real source and optical errors) that is incident on a perfect concentrator.

In a solar concentrator several statistically independent factors contribute to the optical error: contour errors, tracking errors (when averaged over time), deformation and displacement of the receiver, and lack of perfect specularity (6).

Each error type can be characterized by its rms angular width (one-sided deviation from the design direction). The rms width for the total optical error is obtained by adding the squares of the individual widths:

$$\sigma^2_{optical} = 4\sigma^2_{contour} + \sigma^2_{specular} + \sigma^2_{displacement} + \sigma^2_{tracking}. \qquad [2\text{-}2]$$

($\sigma_{contour}$ is multiplied by two because of Snell's law).

Note that this rule for combining standard deviations is valid regardless of the shape of the individual error distributions; they could be Gaussian, boxlike, or anything else since all distributions under discussion have zero mean. The total beam width σ is obtained by adding the rms width of the sun according to

$$\sigma^2 = \sigma^2_{optical} + \sigma^2_{sun}. \qquad [2\text{-}3]$$

Measurements of reflector surfaces have shown that the distributions corresponding to $\sigma_{contour}$ and $\sigma_{specular}$ can be treated as Gaussian. The other terms may or may not be Gaussian. However, when many statistically independent distributions are convoluted, the result is nearly Gaussian unless a single non-Gaussian contribution dominates (7). In the case of focussing solar collectors, the Gaussian contour errors appear to be the largest, and a Gaussian approximation for the total optical error is reasonable.

Therefore, the equivalent source (convolution of sun and optical errors) is given by

$$B_{effective}(\theta_\perp) = \int_{-\infty}^{\infty} d\theta'_\perp B_{sun,linear}(\theta_\perp - \theta'_\perp) \times \frac{\exp(-\theta'^2_\perp/2\sigma^2_{optical})}{\sqrt{2\pi}\,\sigma_{optical}} \qquad [2\text{-}4]$$

where $B_{sun,linear}(\theta_\perp)$ is the linear brightness distribution of the sun (in W/m^2 rad) obtained from the circumsolar scans of the Lawrence Berkeley Laboratory (8). In terms of the radial scans, $B_{radial}(\theta)$, measured by Lawrence Berkeley Laboratory, the linear brightness distribution is

$$B_{sun,linear}(\theta_\perp) = \int_{-\infty}^{\infty} d\theta_\parallel B_{radial}\left([\theta^2_\parallel + \theta^2_\perp]^{1/2}\right)$$

To obtain the dimensionless intercept factor, Eq. [2-4] must be normalized by the beam irradiance I_b of the sun (measured by a pyrheliometer):

$$I_b = \int_{-\infty}^{\infty} d\theta_\perp B_{sun}(\theta_\perp). \qquad [2\text{-}5]$$

For simplicity we have replaced all integration limits by infinity, assuming that the distributions are negligible beyond a few degrees. The intercept factor corresponding to a misalignment angle θ_m is

$$\gamma(\theta_m) = \int_{-\infty}^{\infty} d\theta_\perp\, f(\theta_m - \theta_\perp)\, B_{effective}(\theta_\perp)/I_b. \qquad [2\text{-}6]$$

To standardize the tests described in this paper, it is best to take data only when the sky is very clear. The rms width of the sun under such conditions is

$$\sigma_{sun} = 2.6 \pm 0.1 \text{ mrad} \qquad [2\text{-}7]$$

for line focus geometry. This is narrow enough to justify a Gaussian approximation even for the equivalent source, Eq. [2-4], provided the optical errors are on the order of 5 mrad or larger. Since this is the case for the current generation of line focus parabolic collectors, we have made this approximation for the data analysis in this paper. The resulting intercept factor is

$$\gamma(\theta_m) = \int_{-\infty}^{\infty} d\theta_\perp \, f(\theta_m - \theta_\perp) \frac{\exp\left(-\theta_\perp^2/2\sigma^2\right)}{\sqrt{2\pi}\,\sigma} \quad [2\text{-}8]$$

with the total width σ of Eq. [2-3].

Due to reflection and absorption losses the radiation incident on the collector is attenuated by a factor $(\rho\tau\alpha)$ where

- ρ = reflectance of reflector;
- τ = transmittance of receiver glazing, if any; and
- α = absorptance of absorber.

(The parentheses indicate that the factor is an effective transmittance-reflectance-absorptance product, including secondary effects such as multiple reflections.) When the absorber surface is at ambient temperature the heat loss is zero and the efficiency η equals the optical efficiency:

$$\eta(\theta_m) = \eta_o(\theta_m) = (\rho\tau\alpha)\ \gamma(\theta_m). \quad [2\text{-}9]$$

If the heat loss is not zero, an appropriate correction must be applied. Variation of $(\rho\tau\alpha)$ with θ_m is sufficiently small to be negligible for the present purpose.

Figure 2-1 shows schematically what the angular scan looks like for a parabolic trough with cylindrical receiver, rim angle ϕ = 90°, and concentration ratio C=25, for three values of the optical error: 0, 5, and 10 mrad. From these curves one sees that this test is most sensitive to data taken around the curved portion of the graph; data corresponding to the halfway point, on the other hand, do not provide any information on $\sigma_{optical}$.

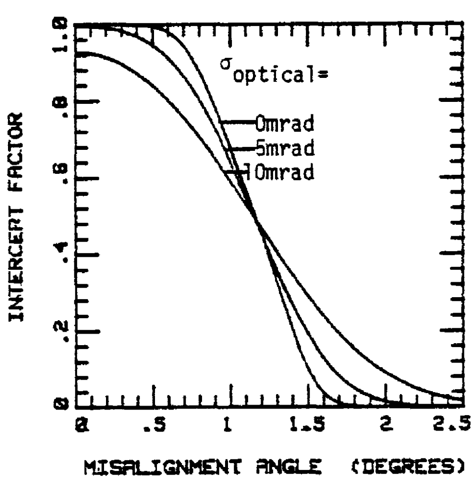

Fig. 2-1. Intercept factor vs. misalignment angle for $\sigma_{optical}$ = 0, 5, and 10 mrad.

3. EXPERIMENT

Since $\gamma(\theta_m)$ depends on σ it is clear that an angular scan of $\eta(\theta_m)$ versus θ_m contains enough information to determine both $(\rho\tau\alpha)$ and σ, at least in principle. In order to determine whether this method is accurate enough to be useful in practice, we decided to test a parabolic trough collector manufactured by Hexcel (9). The test setup is described in another publication (10). The collector has a cylindrical receiver coated with black chrome. The heat shield and receiver glazing originally supplied by Hexcel were removed for this test, so $(\rho\tau\alpha)$ is simply $\rho\alpha$. The reflector is made of an aluminum honeycomb substrate, coated with FEK-163, an aluminized second-surface acrylic film manufactured by the 3M Corporation. The rim angle of the collector is ϕ = 72°, and the geometric concentration ratio is C = 20.9. The tracking axis is horizontal in the east-west direction and the tests were carried out at solar noon, so that the longitudinal incidence angle $\theta_\parallel$ vanishes.

A typical scan of $\eta_o(\theta_m)$ versus θ_m is shown in Fig. 3-1. Positive and negative values of θ_m have been included on the same side because of symmetry. Plotting $+\theta_m$ and $-\theta_m$ together has the advantage of pointing out any systematic error in the zero alignment. A nonlinear least-squares fit to these data yields the values

$$F'\rho\alpha = 0.69 \quad [3\text{-}1]$$

and

$$\sigma = 6.5 \text{ mrad}. \quad [3\text{-}2]$$

(In the test procedure, inlet and outlet temperatures of the fluid were measured, and only the product $F'\eta_o$ of heat extraction ef-

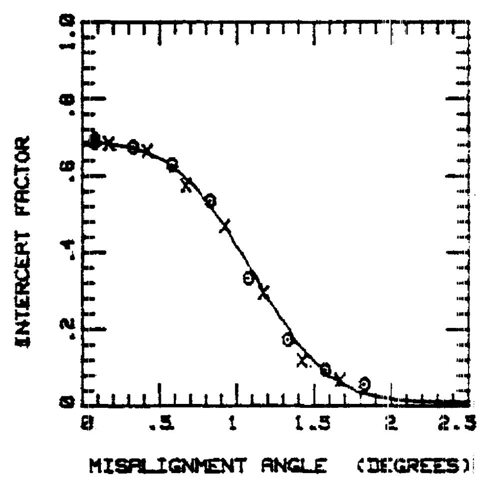

Fig. 3-1. Test data of optical efficiency vs. misalignment angle. ● = positive angles; x = negative angles; solid line = best fit.

ficiency and optical efficiency could be determined.

The theoretical scan corresponding to these parameters is shown by the solid line. To evaluate the accuracy of this method, the scan was repeated several times, and $F'\rho\alpha$ and σ were calculated for each scan. The results are

$F'\rho\alpha$	σ (mrad)
0.66	6.1
0.69	6.8
0.69	6.5
mean 0.68	mean 6.5 [3-3]

The sample standard deviation for the three σ measurements is 0.2 mrad, and gives some indication of the accuracy and reproducibility. However, a sample of three is not large enough for any reliable statistics, and we conservatively estimate the accuracy as ±0.5 mrad, i.e., 10% relative error.

In these tests the misalignment angle was monitored quite accurately, hence the tracking error does not contribute significantly to the beam spread and

$$\sigma^2_{optical} = 4\sigma^2_{contour} + \sigma^2_{specular} + \sigma^2_{displacement} \qquad [3-4]$$

Assuming an rms width of 2.6 mrad for the sun, one therefore obtains from Eq. [2-3] the optical error

$$\sigma_{optical} = (6.5^2-2.6^2)^{1/2}\,\text{mrad} \qquad [3-5]$$

$$= 6.0 \pm 0.5\ \text{mrad}$$

for this experiment.

Unfortunately we did not have a laser ray trace apparatus for an independent evaluation of the optical error. However, measurements of $\sigma_{specular}$ and $\sigma_{contour}$ have been reported by Sandia Laboratories for reflectors also manufactured by Hexcel of a similar type but different focal length (1,11, 12). The contour error ranged from 1.8 mrad before environmental exposure to 2.2 mrad after three months in an environmental test chamber. The value of $\sigma_{specular}$ depends very much on how the FEK-163 film is bonded to the substrate; a value of 1 mrad is possible (12).

If these values of $\sigma_{contour}$ and $\sigma_{specular}$ were applicable to the Hexcel collector tested at SERI, they would imply that the contribution $\sigma_{displacement}$, caused by displacement of the receiver and deformations of the parabola, is fairly large, on the order of 4 mrad. Visual inspection of the solar image at the receiver shows that the reflector is deformed; its curvature tends to be less than the design shape either because of the manufacturing process or because of weight induced sag. A value of 4 mrad for the associated beam spread may be realistic. In view of the difficulty of measuring $\sigma_{displacement}$ directly, and in view of the lack of laser ray trace data for the collector tested at SERI, one can invoke the Sandia data only for a qualitative comparison. To this extent our results are certainly consistent with the Sandia data.

NOMENCLATURE

$B_{effective}(\theta_\perp)$	Equivalent source obtained as convolution of B_{sun} with error distribution (W/m^2 rad)
$B_{radial}(\theta)$	Angular brightness distribution of sun for point focus geometry (W/m^2 sterad)
$B_{sun}(\theta_\perp)$	Angular profile of sun for line focus geometry (W/m^2 rad)
C	Geometric concentration ratio (for example, a trough of aperture width D and receiver tube diameter d has $C = D/\pi d$)
$f(\theta_\perp)$	Angular acceptance function for perfect optics
I_b	Beam irradiance as measured by pyrheliometer (W/m^2)
α	Absorptance of receiver
$\gamma(\theta_m)$	Intercept factor if collector is misaligned; that is, with its optical axis pointing an angle θ_m away from the sun
η	q_{net}/I_b = collector efficiency
η_o	Optical efficiency = $(\rho\tau\alpha)\gamma$
$\theta_\perp$	Projection of incidence angle on plane perpendicular to tracking axis
$\theta_\parallel$	Projection of incidence angle on plane of tracking axis and optical axis
θ_m	Angle from center of sun to plane of symmetry of collector
$(\rho\tau\alpha)$	Effective reflectance-transmittance-absorptance product of collector
$\sigma_{contour}$	rms angular deviation of contour from design direction

$\sigma_{displacement}$	Equivalent rms angular spread that accounts for imperfect placement of receiver
$\sigma_{specular}$	rms spread of reflected beam due to imperfect specularity of reflector material
$\sigma_{optical}$	rms angular spread caused by all optical errors
σ_{sun}	rms angular width of sun in line focus geometry
σ	Total rms beam spread
τ	Transmittance of collector glazing, if any
ϕ	Rim angle

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