OPTICAL CHARACTERIZATION OF CPC CONCENTRATOR BY AN INVERSE ILLUMINATION METHOD

A. Parretta*[1,2], A. Antonini[2,3], M. Stefancich[3,4], G. Martinelli[2], M. Armani[5]
[1]ENEA Centro Ricerche "E. Clementel", Via Martiri di Monte Sole 4, 40129 Bologna (BO), Italy.
[2]Physics Department, University of Ferrara, Via Saragat 1, 44100 Ferrara (FE), Italy.
[3]CPower SRL Via Saragat 1, 44100 Ferrara (FE), Italy.
[4]CNR c/o Physics Department, University of Ferrara, Via Saragat 1, 44100 Ferrara (FE), Italy.
[5]Institute for Renewable Energy, EURAC research, Viale Druso 1, 39100 Bolzano (BZ), Italy.
*Phone: +39 (0)51 6098617; Fax: +39 (0)51 6098767; E-mail: antonio.parretta@bologna.enea.it

ABSTRACT: In this paper we present a characterization method of CPC solar concentrators, based on an inverse illumination procedure, according to which a Lambertian light source is produced at the exit aperture (the receiver aperture) and the emerging light beam is analysed at the CPC input aperture in terms of radiant intensity as function of output direction. The method has been applied by illuminating by a laser a high reflectivity Lambertian diffuser at the receiver port. It follows the recording by a CCD of the light irradiance map produced on a plane screen moved between the CPC and the laser source. Optical simulations have demonstrated that, when the entire surface diffuser is illuminated, the method produces an irradiance intensity map directly correlated to the angle resolved optical efficiency (transmittance) of the concentrator, from which the acceptance angle can be derived. Different types of CPC-like nonimaging concentrators were characterized, as simply truncated CPCs and more innovative optical units used in concentrator photovoltaic modules. Simulated and experimental results demonstrate the validity and simplicity of the proposed inverse method.
Keywords: Nonimaging Optics, Characterization, Concentrators, Modelling, Optical Properties, Ray Tracing.

1 INTRODUCTION

The optical characterization of a CPC concentrator [1-4] can be performed by using a "direct" method, that is illuminating the input aperture with a collimated light beam characterized by a solar divergence (~ 0.27°) and by measuring the flux collected at the exit aperture. If the input flux is known, the angle-resolved optical efficiency (transmittance) of the concentrator is obtained by changing the orientation of the concentrator with respect to the beam, from which the acceptance angle can also be derived. Fig. 1a illustrates the "direct" method of illumination. The light source (ls) illuminates the integrating sphere (is1), which acts as a source of diffuse light at window (w), of diameter D_w. A portion of light emerging from the sphere is collected by the parabolic mirror (pm1), oriented slightly off-axis with respect to (w) and at a distance equal to its focal length, f. The mirror (pm1) produces a parallel beam with angular divergence controlled by the ratio f/D_w , which must be ~100 for simulating the solar divergence. The parallel beam illuminates the solar concentrator (lc) and the light at the exit aperture of (lc) is directed to a second integrating sphere (is2) where the flux is measured by photodetector (pd) and radiometer (ra). To measure the absolute optical efficiency, also the flux incident at entrance of the concentrator must be measured. This is done with the experimental setup of Fig. 1b, where the (lc) is replaced with a second parabolic mirror (pm2) which focalizes the collimated beam on the same integrating sphere (is2) for flux measurement. If the reflectivity R_{pm} of the second mirror is known, the angle resolved efficiency of the concentrator becomes:

$$\eta(\delta) = S_{CPC}(\delta) \cdot \frac{(1 - R_{pm})}{S_{ref}} \qquad (1)$$

with δ angle of incidence, $S_{cpc}(\delta)$ flux signal measured with the setup of Fig. 1a and S_{ref} flux signal measured with the reference setup. The direct method has been simulated by using the TracePro® software for opto-mechanical modelling [5]. Fig. 2 shows the optical efficiency curves obtained by simulating an ideal 3D-CPC [4] with δ_{acc}=5° acceptance angle, 1-cm exit aperture diameter and two wall reflectivities R_w: 0.95 and 1.0. The other dimensional parameters of the CPC are: 11.5-cm input aperture diameter, 71.3-cm length. The efficiency curves are characterized by a flat response at low angles and a sharp drop at the acceptance angle.

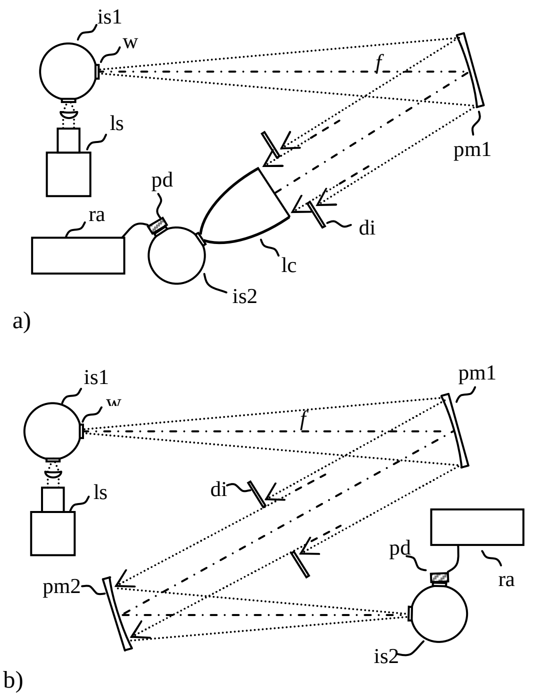


Figure 1: a) Schematic of the "direct" method experimental setup for measuring the flux collected by the concentrator (lc) at different angles of incidence. b) Reference setup for measuring the input flux.

The acceptance angle is generally defined for a drop of efficiency of 50% [4]. For photovoltaic applications it is common to refer to a 10% drop (90% efficiency) [6]. The efficiency curves of Fig. 2 needed a long series of simulations (21 in the examples). As many measurements should be done if the direct method would be applied experimentally. In this paper we introduce an alternative way to measure the optical efficiency of the CPC, based on an "inverse" illumination procedure, whereby the CPC exit aperture is used for placing a diffused light source directed towards the CPC inside, and the radiant flux exiting from the CPC input aperture is measured at different directions in space.

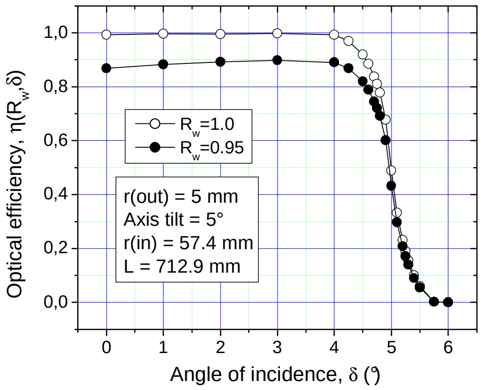


Figure 2: Absolute optical efficiency (transmittance) curves obtained by raytracing an ideal 3D-CPC concentrator with 5° acceptance angle, at wall reflectivities R_w=1.0 and 0.95.

We show in this paper that this "inverse" method of illumination is a powerful means of characterization, requiring just one simulation or measurement run to derive the optical efficiency curve. It is attractive also for its simplicity, requiring a spatially limited light source (i.e. a laser). We show also how to transform it in a flexible tool for optical investigation of nonimaging concentrators, adopting the criterion of local illumination of the diffuser.

2 THE BASIC INVERSE METHOD

Fig. 3 shows the basic scheme of the "inverse method". It will be henceforth referred to as ILLUME (Inverse ILLUMination MEthod). The output aperture (oa) of CPC is closed with a high reflectivity Lambertian diffuser (ld). A collimated beam (ib), aligned with the optical axis z, illuminates the entire target area facing the CPC. The incident light is back reflected off the target towards all directions inside the CPC and diffused outside from input aperture (ia). The output beam (ob) is then projected on a plane screen (sc) for visual observation and the irradiance distribution recorded by a CCD. In an alternative scheme, the input beam can be applied from the backside of the concentrator and the high reflectivity diffuser (ld) is replaced by a semitransparent diffuser with Lambertian transmission properties. As light rays are emitted by diffuser (ld) towards the front side of the CPC from all possible directions, we deduce that the bundle of rays forming the output beam (ob) must correspond to the family of all possible rays which, from the opposite direction, should be able to reach the receiver and then to be collected by the CPC under direct illumination conditions.

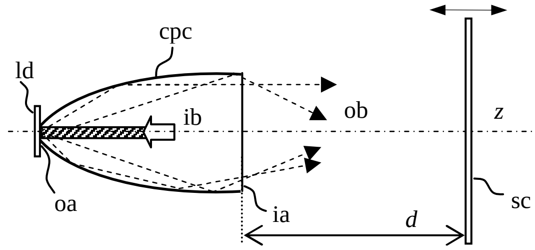


Figure 3: Schematic principle of the inverse illumination method (ILLUME).

The inverse method, therefore, provides a bundle of rays (ob) bringing all the information related to the collection properties of the CPC and, in particular, the information of the acceptance angle. If $E(\delta, x)$ is the irradiance in W/cm^2 on the screen surface at distance x from z axis, and the screen (sc) is far from the CPC, $d >> a$, with a radius of the CPC input aperture (ia), then the radiance for an ideal CPC can be expressed as:

$$\mathrm{L}(\delta) = \mathrm{L}(\mathrm{d}, \mathrm{x}) = \mathrm{E}(\mathrm{d}, \mathrm{x}) \cdot \frac{\mathrm{d}^2}{\cos^4\left[\mathrm{tg}^{-1}\left(\frac{\mathrm{x}}{\mathrm{d}}\right)\right]} \qquad (2)$$

Normalizing $E(\delta, x)$ to $E(\delta, 0) = L(0)/d^2$, we obtain the relative radiance $L_{rel}(\delta)$:

$$\mathrm{L}_{\mathrm{rel}}(\delta) = \frac{\mathrm{L}(\delta)}{\mathrm{L}(0)} = \mathrm{E}_{\mathrm{rel}}(\mathrm{d}, \mathrm{x}) \cdot \frac{1}{\cos^4\left[\mathrm{tg}^{-1}\left(\frac{\mathrm{x}}{\mathrm{d}}\right)\right]} \qquad (3)$$

The relative radiance $L_{rel}(\delta)$ equals the relative optical efficiency $\eta_{rel}(\delta)$ of the CPC concentrator. In fact, inverting the direction of rays, $L_{rel}(\delta)$ corresponds to the relative (to $\delta = 0°$) flux collected at the CPC exit aperture from a plane wave incident on the CPC input aperture at δ angle.

3 APPLICATIONS OF THE INVERSE METHOD

Optical simulations and experimental characterizations have been performed on some CPC-like concentrators, as ideal CPC concentrators, simply truncated CPCs and truncated and squared CPCs. In this paper we report the results obtained with ideal CPC concentrators and truncated and squared CPCs (TS-CPCs). In both cases the results demonstrate the correctness of presented theory and then the validity of the proposed inverse method.

3.1 Ideal CPCs

We have modelled by ILLUME the ideal CPC with R_w=1.0 introduced in Section 1. With the screen (sc) very far from the CPC, we have obtained the irradiance profile $E(\delta, x)$. From the irradiance profile, applying Eq. (3), we have extracted the average radiance along x and y directions and derived the average relative efficiency $\eta_{rel}(\delta)$ towards the same directions (see Fig. 4), finding an acceptance angle of 5.0°±0.1°, the same obtained by the efficiency curve of Fig. 2 at R_w=1.0. This simulation demonstrates that the ILLUME method gives, in a different way, exactly the same result obtained with the direct illumination method.

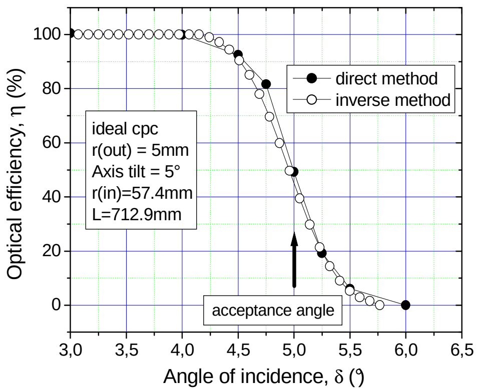


Figure 4: Optical efficiency curves of an ideal CPC, calculated by following both the direct (black circles) and the inverse (white circles) illumination method.

3.2 Truncated and Squared CPC (TS-CPC)

Fig. 5 shows the CAD of a truncated and a squared CPC (TS-CPC). The original CPC was truncated to reduce its length and its input aperture was squared to obtain an external shape suitable to reach high packing efficiency when assembling these units in a module [7]. The TS-CPC has a squared input aperture of 10-cm side, a circular output aperture of 1-cm diameter and a 35-cm length. The squaring process produces four planar surfaces which meet at the vertices of the squared aperture. These four surfaces have a strong effect on the optical properties of the concentrator.

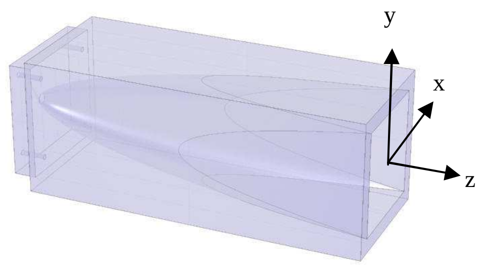
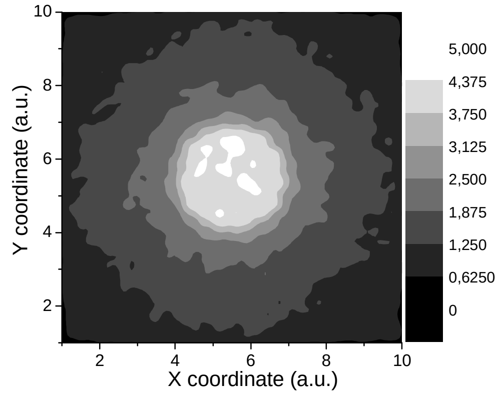


Figure 5: CAD image of the TS-CPC concentrator.

The irradiance map, produced on a 500-cm side squared screen (sc) 3000-cm far from the CPC, and the corresponding average profile measured at the centre of the screen along x and y directions, are shown in Fig. 6. The simulated relative efficiency $\eta_{rel}(\delta)$ of the TS-CPC is finally obtained from the irradiance profile by applying Eq. (3) (see Fig. 7, white circles). Fig. 7 compares the ILLUME $\eta_{rel}(\delta)$ curve with that obtained by simulating the direct method (dark circles): the agreement is excellent. We find for the inverse method 1.4° and 2.1° as acceptance angles at 90% and 50% efficiency, respectively; the correspondent angles for the direct method are 1.5° and 2.3°.



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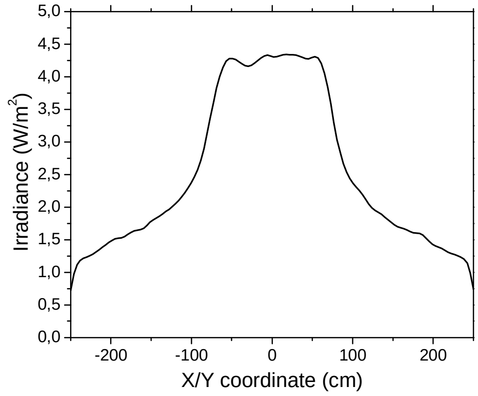

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Figure 6: a) Irradiance map of the TS-CPC concentrator. b) Average x/y profile at the centre of the screen (right).

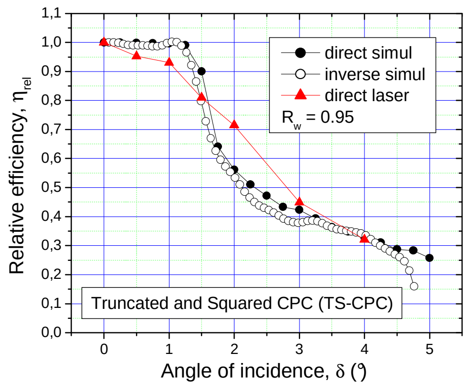
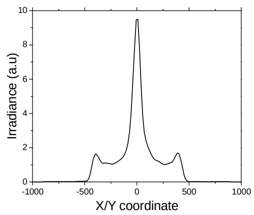


Figure 7: Relative optical efficiency $\eta_{rel}(\delta)$ of TS-CPC obtained by the direct method (dark circles) and the inverse method (white circles).

The ILLUME method becomes a powerful tool of investigation of the optical properties of the concentrator if the diffuser is locally illuminated. In this way in fact we are able to derive the relative efficiency curve $\eta_{rel}(\delta)$ specific of the illuminated area and to establish the range of incidence angles at which that region collects light (is illuminated) by a plane wave at input with less or more efficiency. An example of this procedure is given here simulating the inverse illumination of the centre of the diffuser of TS-CPC by a collimated beam with variable

cross section. The irradiance profiles, $E(d,x)$ and $E(d,y)$, recorded on a 2000-cm-side squared screen 3000-cm-far from the TS-CPC, have been averaged and reported in Fig. 8 at increasing values of the beam cross section radius. The last radius (5 mm) is that required to illuminate the entire diffuser surface. In this case we obtain the same irradiance profile illustrated in Fig. 6b. The angular interval spanned by the profiles is ±18.4°. It is interesting to note that, reducing the beam cross section radius, the efficiency curve reduces in width and increases in height (about twice); as a consequence, also the acceptance angle is reduced. This means that at an inverse beam restricted at the centre of the diffuser in the exit aperture corresponds a direct beam at input aperture more aligned with the z optical axis. This is well known in the science of nonimaging optics, that is a beam well collimated with the optical axis of the CPC (δ = 0°) produces an intense irradiation in the very centre of the receiver. The thinning of the central profile in Fig. 8 goes with the appearing of two satellite bands at ±7.2°. At this angles the square aperture begins the shadowing of the circular receiver respect to an incoming direct beam.
Experimental measurements were also made by illuminating with a lamp the TS-CPC on the back side through a semitransparent diffuser (ld). The light diffused from the front of the CPC was thrown on a white screen 345-cm far apart. Fig. 9 shows the light image produced on the screen and recorded by the CCD camera.



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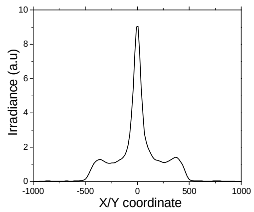

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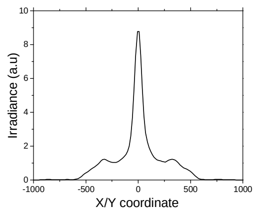

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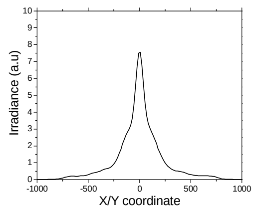

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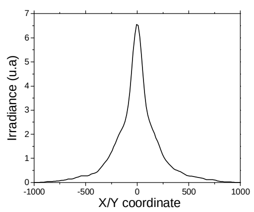

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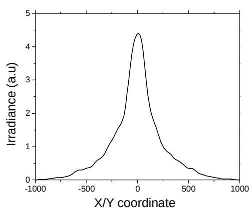

f)

Figure 8: Irradiance profiles obtained by simulating the inverse method for the TS-CPC concentrator. The profiles were averaged along x and y axis directions, parallel to input aperture edges (see Fig. 5), for different values of the input beam radius R: a) R = 0.05 mm (scale 10 W/m^2); b) R = 0.5 mm (scale 10 W/m^2); c) R = 1.0 mm (scale 10 W/m^2); d) R = 2.5 mm (scale 10 W/m^2); e) R = 3.5 mm (scale 7 W/m^2); f) R = 5.0 mm (scale 5 W/m^2).

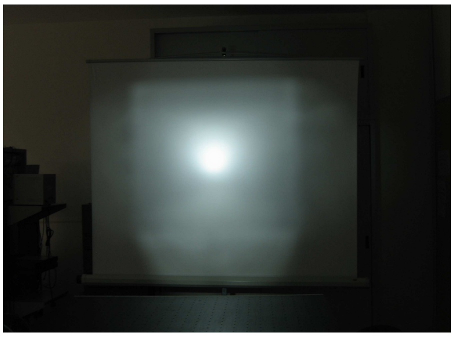

Figure 9: Irradiance CCD image of light diffused on the screen (sc) by the TS-CPC illuminated in the inverse mode (ILLUME).

The squared contour is consequence of the squared entrance window (ia). Light protracts over the squared contour as an effect of reflections on the four planar walls. At the centre of the image a strong circular spot is produced. The average intensity profile along x (horizontal) direction crossing the circular spot has been then obtained from the digitized CCD image (see Fig. 10). From the profile of the relative radiance we derive an acceptance angle of 0.8° at 90% efficiency and 1.9° at 50% efficiency.

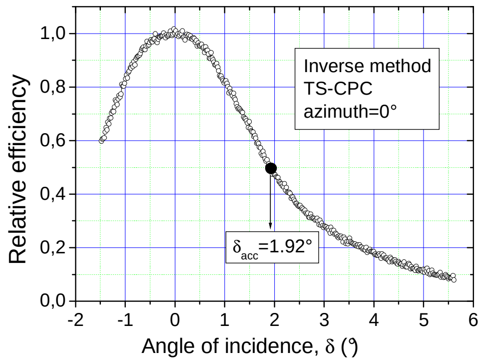

Figure 10: Relative radiance profile $I_{rel}(\delta)$, calculated applying Eq. (3) to the relative irradiance $E_{rel}(d, x)$ measured on the screen surface. The radiance profile corresponds to the relative efficiency $\eta_{rel}(\delta)$ of the CPC concentrator.

4 CONCLUSIONS

In conclusion, we have introduced a new method of characterization of solar concentrators, called ILLUME, whose experimental setup is very simple to realize, requiring only a laser or a lamp and a digital camera or a CCD. By this method, a single simulation or a single experimental measurement is sufficient to determine the relative optical efficiency and the acceptance angle of the concentrator. We have tested the ILLUME method on different types of nonimaging concentrators, by simulations with commercial optical codes and by experimental measurements. In all cases, the optical efficiency and the acceptance angle were consistent with those attainable with conventional optical methods of characterization.

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