Direct and Inverse Methods of Characterization of Solar Concentrators

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Abstract: We discuss two classes of methods for characterizing solar concentrators (mainly nonimaging): "direct" and "inverse", in relation to the way these are irradiated. We derive the optical collection efficiency under collimated and diffused light.

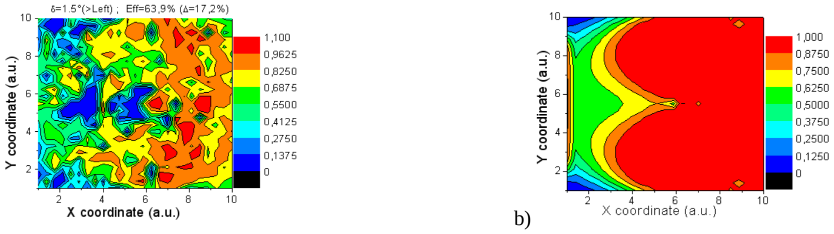
OCIS codes: (220.1770) Concentrators; (220.4840) Testing; (220.4298) Nonimaging optics

1. Introduction

Several methods can be applied to the optical characterization of solar concentrators. In this paper we focus our attention to two classes, directly derived by our research on this subject: "direct" and "inverse", distinguished by the way the concentrator is irradiated, if from the input or the output aperture, respectively. In this sense, the term "direct" is by no means to be associated to the direct component of solar radiation. We will investigate mainly concentrators derived by the nonimaging optics, like the well known Compound Parabolic Concentrators (CPC) [1], with ideal or modified shape, to reduce its length or to optimize its packing in a module [2].

2. The direct methods

The simplest direct method (laser method, LM) uses a laser beam to scan the input aperture following a matrix of points at fixed orientation direction (zenithal and azimuthal angles δ, ϕ) [3]. The flux measured at output aperture allows to draw the map of "local" transmission efficiency, that, when compared to the simulated map carried out on the CAD model of concentrator, gives information about local surface/interface defects or manufacturing inaccuracies of the substrates. An example of this map for a CPC with square-shaped input aperture and reflective walls realized by strips of 3M VM2000 radiant mirror films is shown in Fig. 1. By placing a suitable scattering globe at output aperture, the laser method allows to measure also the direction of output beam [3].



a) b)

Figure 1. a) Example of the experimental LM map obtained at 1.5° incidence of laser beam for a CPC with square-shaped input aperture [3]. b) The same map as obtained simulating the LM by an optical code on the CAD model.

The angle-resolved transmission efficiency of the whole concentrator is obtained irradiating the entire input aperture by a suitably oriented parallel beam and measuring the output flux (Fig. 2a). From the transmission curve we derive the acceptance angle, δ_{acc}, conventionally the angle at 50% of the 0° efficiency (90% for photovoltaic applications) (Fig. 2b). This method is referred to as the "direct method" (DM). It simulates the irradiation of concentrator by the direct component of solar radiation. Fig. 2c shows the DM experimental apparatus during characterization of "Rondine" nonimaging concentrator [4]. The beam from the integrating sphere (is_1) is collimated by parabolic mirror (pm_1) and irradiates the concentrator (cpc). The output flux, measured by the integrating sphere (is_2) at different orientations of the (cpc), gives the relative transmission efficiency $\eta_{dir}^{rel}(\delta, \phi)$. A separate measure on the input beam gives the input flux and then the absolute transmission efficiency $\eta_{dir}(\delta, \phi)$. We introduce now a new direct method performing the integration of transmission efficiency over the input orientation: the "integral direct method" (IDM). IDM simulates the irradiation of concentrator by the diffuse component of solar radiation.

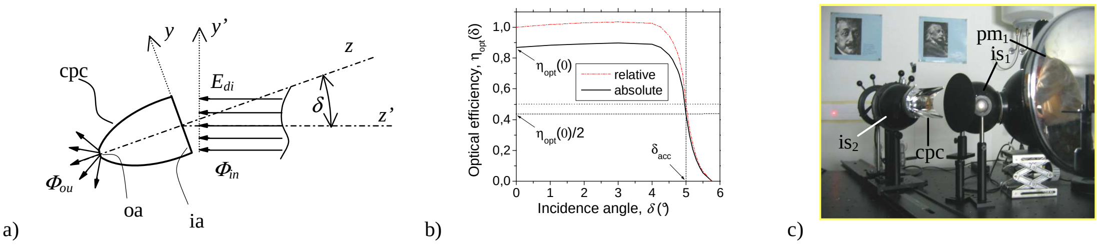


Figure 2. a) Scheme of DM. b) Absolute and relative transmission curves of a 3D-CPC with δ_{acc} = 5° and 95% wall reflectivity. c) DM apparatus.

The optical transmission efficiency by IDM is the integral transmission τ_{dir}^{int}, derived by integrating the angle-resolved optical transmission $\eta_{dir}(\delta, \phi)$ over the input incidence angles (zenithal and azimuthal) δ, ϕ:

$$\tau_{dir}^{\text{int}} = \frac{1}{\pi} \cdot \int_0^{2\pi} d\phi \cdot \int_0^{\pi/2} d\delta \cdot \sin\delta \cdot \cos\delta \cdot \eta_{dir}(\delta,\phi) = \frac{1}{\pi} \cdot \eta_{dir}(0) \cdot \int_0^{2\pi} d\phi \cdot \int_0^{\pi/2} d\delta \cdot \sin\delta \cdot \cos\delta \cdot \eta_{dir}^{rel}(\delta,\phi) \qquad (1)$$

For small size concentrators, the IDM can be carried out indoors by using an integrating sphere to produce a uniform lambertian irradiation over the input aperture (see Fig. 3a). Input and output fluxes can be then measured by alternating a photodetector (pd) on the input and output apertures. The IDM can be carried out also outdoors by simply exposing the concentrator to the diffuse component of solar radiation, after removing the direct component by a shadow band (sb) (see Fig. 3b).

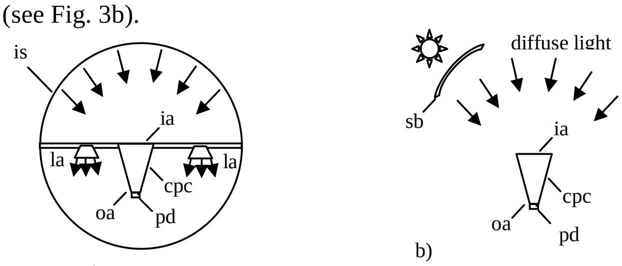


Figure 3. a) Schematic principle of the indoor "integral direct method". The integrating sphere (is) is illuminated by lamps (la). b) Outdoor measurements carried out by exploiting the diffuse component of solar radiation.

3. The inverse methods

With the "inverse" methods we test the concentrator by irradiating the output aperture, therefore reversing the light path occurring during normal operation. The inverse method, IM, as introduced in [5], is an alternative way to obtain the angle-resolved optical efficiency of a concentrator. It is characterized by a remarkable rapidity of measurements and by a simple apparatus with respect to direct method (DM). The "conventional" IM is applied by irradiating the overall output aperture by a lambertian source (Fig. 4a). Light projected from the input aperture over the screen (sc) (Fig. 4b) produces an irradiance distribution $E_{inv}^{rel}(\delta, \phi)$ whose profile, corrected by the $\cos^{-4}(\delta)$ factor, gives the relative radiance $L_{inv}^{rel}(\delta, \phi)$ of concentrator towards (δ, ϕ) direction. It can be demonstrated [5,6] that $L_{inv}^{rel}(\delta, \phi)$ is equivalent to the relative "direct" angle-resolved transmission efficiency $\eta_{dir}^{rel}(\delta, \phi)$ obtained by direct method (DM): $L_{inv}^{rel}(\delta, \phi) = \eta_{dir}^{rel}(\delta, \phi)$. Measurement of $E_{inv}^{rel}(\delta, \phi)$ is done by CCD recording of the image on the screen.

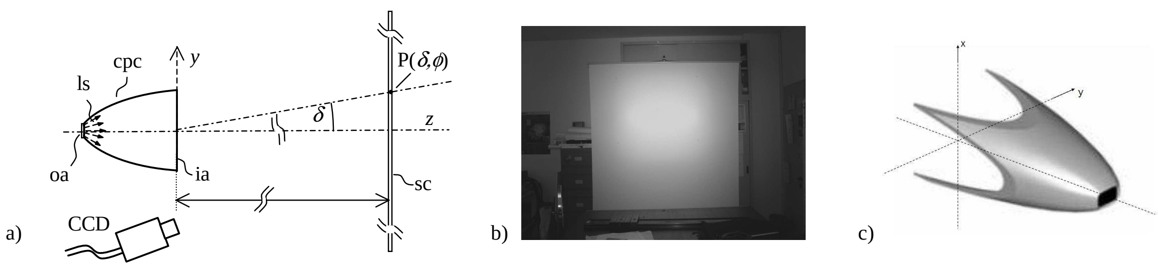
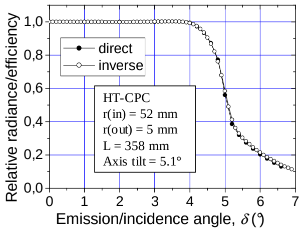


Figure 4. a) Schematic principle of IM. b) Image produced on the screen (sc). c) "Rondine" concentrator



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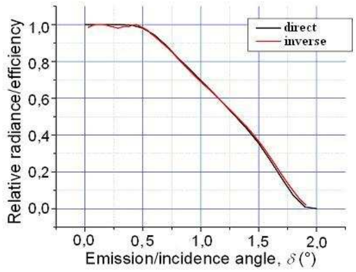
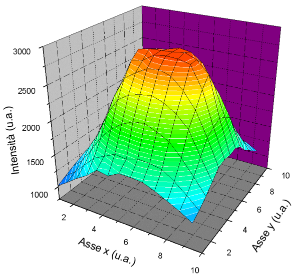


b)

Figure 5. Comparison between relative "inverse" radiance and relative "direct" transmission efficiency obtained by IM and DM simulations for: a) a half-truncated CPC with 5.1° acceptance angle, b) a circular Fresnel lens.

The validity of equivalence: $L_{inv}^{rel}(\delta, \phi) = \eta_{dir}^{rel}(\delta, \phi)$ has been widely demonstrated by us by optical simulations of both DM and IM for several types of concentrators (Fig. 5). Some IM experimental results applied to the "Rondine" concentrator (Fig. 4c) are shown in Fig. 6. Fig. 6a shows the intensity distribution of the recorded image by the screen (sc). After elaboration of this image, we obtain the radiance (transmission efficiency) profiles along horizontal and vertical directions as shown in Fig. 6b, and the corresponding (photovoltaic) acceptance angles: δ_{acc}= 6.3° (horizontal); δ_{acc}= 4.3° (vertical).



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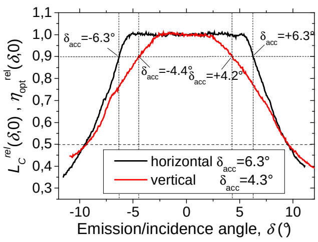

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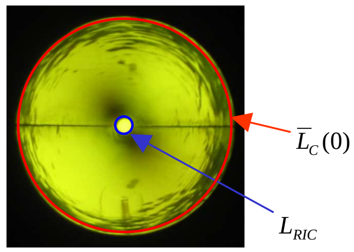

c)

Figure 6. a) Intensity map of the CCD image of "Rondine" concentrator. b) Horizontal and vertical profiles of inverse radiance. c) Measure of radiance on the input aperture of a truncated CPC: $\overline{L}_C(0)$ = average radiance of the whole aperture; L_{RIC} = radiance of receiver.

The IM as applied so far gives the relative optical efficiency of concentrator, $\eta_{dir}^{rel}(\delta, \phi)$. To have the absolute optical efficiency, $\eta_{dir}(\delta, \phi)$, we need to measure $\eta_{dir}(0)$. This can be done by IM orienting the CCD camera towards the concentrator input aperture and measuring its radiance (Fig. 6c). It can be demonstrated that $\eta_{dir}(0)$ is given by the ratio $\overline{L}_C(0) / L_{RIC}$, where $\overline{L}_C(0)$ is the average radiance of the whole input aperture and L_{RIC} is the radiance of the receiver, that is of the lambertian source. The IM can be applied also locally, by irradiating only a portion of output aperture by a lambertian source, therefore becoming the "local inverse method" (LIM). In this way LIM explores the "direct" optical efficiency of different regions of receiver, allowing to establish which directions are more effective for their optical collection in "direct" mode. A final remark about the correct application of IM: light from the inverse lambertian source must be unpolarized. The best way to achieve this is to use an integrating sphere. The alternative is the use of a high reflectivity lambertian diffuser illuminated by the front side of concentrator. The above described methods are generally "indoor" methods. Some of them, like DM and IDM, can be applied also "outdoors" by exploiting the direct or diffuse component of solar radiation, respectively.

4. References

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