Optical test of solar components using solar divergence collimators

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Abstract

The optical characterization of solar components represents a crucial aspect of the research on renewable energies. It allows evaluating the optical features of every single component, taking as reference the optical project. Laboratory tests can comparatively characterize the elements of a serial production, thus giving information about production homogeneity. They can examine solar concentrators of various shapes, dimensions and collection features. The main tests assess collection efficiency, image plane analysis and angle dependence. The core of the laboratory set-up for the tests is a solar divergence collimator, reproducing the sunlight divergence and therefore simulating the operative conditions.

Keywords Solar energy; Optical tests; Concentrators; Optical design

1 - Introduction

Since 1997 optical systems for sunlight concentration on small surfaces have been studied and experimented in our laboratory [1-6]. Our work on renewable energies includes three main research lines: optics to concentrate and transfer solar light by optical fibers, sunlight collectors coupled to PhotoVoltaic cells (CPV systems) and finally solar concentrators coupled to various devices. The possible applications of these systems involve thermal sector, internal illumination and photovoltaic field. An essential aspect of these researches is the optical characterization of the realized solar components [3-4]. The tests are aimed to compare the measured values of optical characteristics to the nominal values belonging to the optical project of the component. Furthermore suitable optical measurements allow checking the homogeneity of collector production, comparing the optical features among the different samples realized on the base of the same optical project.

Our laboratory has developed test configurations and procedures to characterize solar collectors with maximum diameter/diagonal 240 mm. For such reduced sizes the examined components typically have various shapes, dimensions and collection characteristics. Consequently each image presents different light levels and uniformity features, which require the use of appropriate hardware and measurements techniques. The proposed optical characterization of solar collectors assesses image plane analysis, angle dependence, collection efficiency and spot size. These tests provide fundamental information and performance for the solar exploitation; nevertheless on the base of the specific solar application it can be interesting to examine other aspects.

2 - Image plane analysis

The image analyses, as the collection efficiency assessment, require some preliminary studies on the focal distance f. It is fundamental to determine the position of each focal plane, measuring the experimental values of f for each collector sample. The definition of the focal plane is dictated by collector design and solar system application. Solar collectors are optically designed as non-imaging systems with the main purpose of maximizing the focused energy within the nominal image. Hence the focal plane can simply be individuated by maximizing the collected light over the whole examined plane (for absorber size exceeding the nominal image). If the dimension of the absorber is crucial, as in case of PV cells (or optical fibers), the image plane can be defined maximizing the light concentrated over a detector with shape and size of the real absorber. After the determination of the focal distance, several experimental measurements can then be performed to examine the image generated by each sample of a solar collector production. In particular for Concentrating PhotoVoltaic applications it is fundamental to analyze the light distribution in the image plane.

The optical system for the test includes a solar divergence collimator reproducing the divergence of sunlight rays. It can be of two types: C1 (Fig. 1a) for small components, with diameter/diagonal lower than 80 mm, or C2 (Fig. 1b) for larger samples, up to diameters of 240 mm. Figures 1a,b show the two optical systems used for image plane analysis, with a suitable high-definition camera as sensor. The difference between the two layouts is the collimation optics: a lens with focal length f_C=700 mm (diameter d_C=90 mm) in Fig. 1a or a spherical mirror with f_C=1.5 m (d_C=250 mm) in Fig. 1b. In both cases, the source is realized by a white light illuminator coupled to an integrating sphere using an optical fiber. The solar divergence is reproduced combining the sphere output diameter S to the focal distance f_C of the collimation optics. The beam with solar divergence impinges on the sample under test and a camera visualizes the generated image. The high-definition camera is mounted on a mechanical support that is usually displaced by a high-precision translation stage, to keep a good stability of the detection system and to allow a precise estimation of the focal distance. Beside the high precision, the translation stage should have high reproducibility of the positions and large excursion. For our laboratory tests we use a CMOS camera with an external chip, which allows examining collectors with very short focal distances. The image saturation is a critical parameter in these tests. First of all, the source level should be adapted to obtain a good image for the camera acquisition. The detection parameters can be properly chosen to evidence different aspects of the image analysis. For instance the image saturation must be avoided when determining the beam profile. On the other hand, the image saturation can be useful to emphasize image borders. It is important to remark that all these measurements are very sensitive to misalignments between collector plane and camera array plane. Therefore mounting stability and alignment accuracy are essential elements to obtain reliable and reproducible results. To consider some defocusing effects, the mentioned analysis can be repeated examining the parallel planes located before

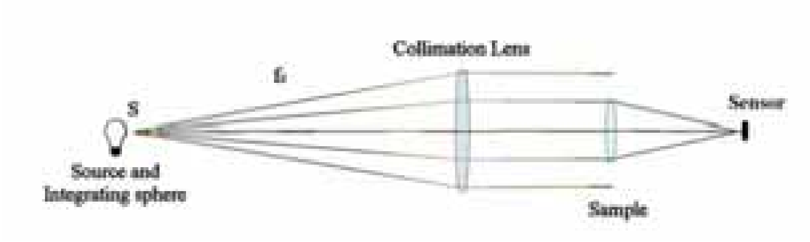

Fig. 1a – C1 for image tests and focused image tests on large samples.

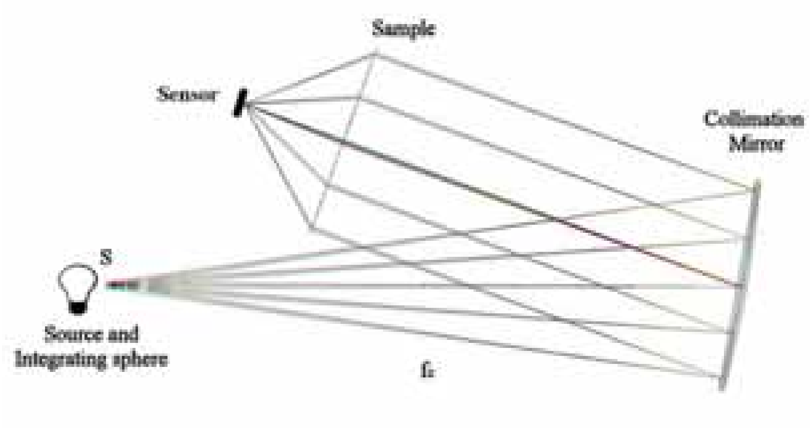

Fig. 1b - C2 for image tests and focused image tests on large samples.

and after the focal position. Moreover dedicated measurements can investigate the dependence on specific parameters of interest.

3 - Angle dependence study

The angular tests examine how collector features and performances are affected by rotations, tilts and angular misalignments in general. These are fundamental aspects to be investigated especially because they are connected to collection efficiency performance, tracking errors and Field of View aperture of the optical system. In the worse case, the angular misalignment can cause bad illumination over the PV cell, generating thermal stresses. Since every collector has its specific collection geometry, it is consequently characterized by specific angular effects and angle dependencies, which can be examined by appropriate tests. Furthermore typically each application has specific angular requirements that can be experimented or verified in laboratory by suitable tests on angle dependence.

To complete the research the angular studies can be combined with image plane analyses or collection efficiency assessment. Investigating the interactions between the separately tested aspects, this experimentation represents a better simulation of the real working conditions. The angular tests basically require a tilt or a rotation stage, which is combined to the instrumentation used for image plane analyses or collection efficiency tests. By a practical point of view, for the simulation of mounting errors or angular misalignments only the collector is rotated. While in the tracking error tests both collector and detector are rotated with the same reference plane.

4 - Collection efficiency test

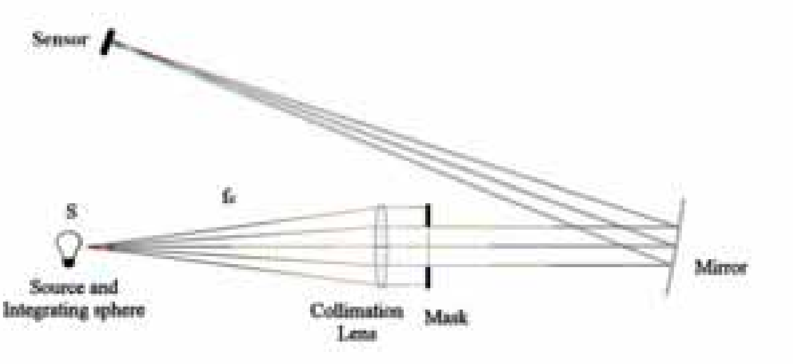

Fig. 2a – C1 for entering light measurement on small components.

For the applications of sunlight exploitation, the essential quantity to be considered is the collection efficiency. The measurements are performed on a white light collimator that reproduces the solar light divergence assessing the efficiency of solar light collection. The collection efficiency is obtained as ratio between the light focused within the nominal image and the light inside the entrance aperture of the collector. These two quantities are separately measured. The focused light is measured using the optical set-up of Fig. 1a (for small collectors) or Fig. 1b (for large collectors). For this measurement the sensor is a photodetector with dimensions corresponding to the nominal image, obtained from the optical project of the tested collector. The beam with solar divergence illuminates the sample under test, which is located at the focal distance to maximize the collected light.

The second measurement concerns the light entering through the collector entrance aperture and it is performed using the optical systems in Fig. 2a (for small collectors) or Fig. 2b (for large collectors). The beam with solar divergence impinges on a suitable mask, composed of a screen with a hole reproducing shape and size of collector entrance aperture. The light passing through the mask is concentrated by a spherical mirror and measured by a photodetector. In general the optical tests are aimed to verify homogeneity of collector production and reproducibility of the collector fabrication process. Every test checks production homogeneity and reproducibility for the specific aspect examined by the test; but probably the most significant results are represented by collection efficiency assessment and focal distance measurement. The essential optoelectronic instrumentation employed to assess the collection efficiency is a photodiode with large dynamic amplifier, a mask (simulating the collector entrance aperture), a concentrating mirror (spherical mirror) and a translation stage. The optical systems of Fig. 1a and Fig. 2a are used to measure collectors with maximum diagonal/diameter 80 mm. Components of larger dimensions are tested with the configurations of Fig. 1b and Fig. 2b. The current mirrors available in our laboratory have diameter 250 mm and they allow testing samples with maximum diameter 240 mm. The photodetector used in our laboratory set-up is a squared photodiode of side 18 mm. In the measurement of entering light the image diameter of the source S on the photodiode exceeds 15 mm, therefore the photodiode should have suitable dimensions. This is due to the fact that the source diameter S is dictated by the requirements of solar divergence reproduction and by the focal length of collimation optics. An important aspect is to utilize the central portion of the collimated beam, characterized by higher uniformity. The reflectivity of the concentrating mirror should be assessed especially because they typically are large mirrors with diameters of 200-300 mm. Moreover the reflectivity is not constant over the reflecting surface; hence we usually estimate an average value, which is successively employed to rescale the detection. Finally the entering light measurement can be replaced by a light density assessment if the beam is homogeneous enough.

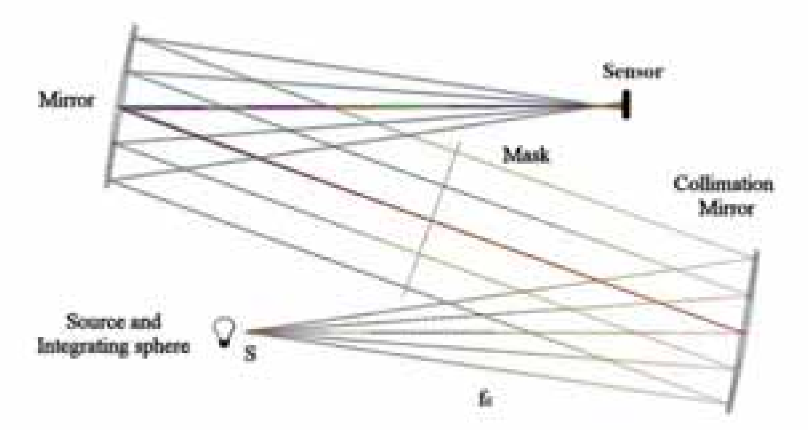

Fig. 2b – C2 for entering light measurement on large components.

5 - Image size measurement

A simple and low-cost methodology allows evaluating the light concentrated into a fiber or over a PV cell. This experimental measurement assesses image spot dimension and light distribution within the focused image. The optical set-up for this image control includes a white light source reproducing the solar divergence. The beam impinges on the tested collector and a detection system is located in its image plane. It consists in a photodiode combined to a multi-holes mask: a mask with 8 hole diameters d, with step of 0.1 mm, is suitable for images of few millimeters. The mask moves in front of the detector and it allows measuring the light intensity Id corresponding to the encircled image, which is the luminous intensity focused inside a hole. This image analysis can verify if the collector production is homogeneous for what concerns the light distribution inside the image. The results are expressed, in percentage, as ratio between encircled image light and total light in the focal plane. Some measured results appear particularly interesting: the diameter

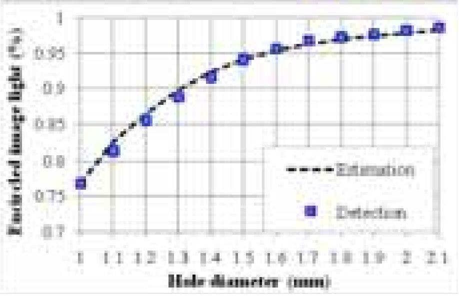

Fig. 3 – Practical and theoretical encircled image light.

pertaining to the nominal image of the collector and the value corresponding to the absorber (core diameter of the optical fiber or PV cell area).

The technique to determine the image diameter Di is based on the measurement of the encircled image light Id. The value of Di is obtained when the Id values start to saturate, thus indicating that the hole diameter d is exceeding Di. Some Id results are reported in Fig. 3, plotting Id versus d. For verification Fig. 3 also reports the corresponding values estimated from an image acquired by a CMOS camera. Considering a saturation threshold of 95%, for the curve in Fig. 3 the value of image diameter Di is 1.6 mm. In this test the translation stage moves the multi-holes mask behind the collector, which keeps its position. The most critical point for this measurement is the alignment of each hole. The multi-holes mask should be moved in the image plane, keeping the hole in the focal position, which is practically obtained maximizing the photodiode output signal. This procedure can be applied when the image is unusable for the camera: in case of very luminous or extremely poor signal.

6 - Aberrations of solar divergence collimators

Optical collimators reproducing the solar divergence represent the core of the laboratory set-up employed to characterize solar components. In all layouts for the optical tests the source is realized by a white light illuminator coupled by an optical fiber to an integrating sphere. The solar divergence is reproduced combining the sphere output diameter S to the focal distance of collimation lens f_C. The beam with solar divergence impinges on the sample under test and a sensor examines the generated image: a CCD camera image plane analyses or a photodetector for collection efficiency assessment. Size and shape of the photodetector should correspond to those of the absorber. The solar divergence collimator can be realized in axis (C1) if the examined collectors have reduced dimensions. For practical reasons, the test of solar collectors with diameter exceeding 80 mm is realized employing collimator C2. It has two spherical mirrors: the first acts as collimation mirror while the second is a concentrating mirror. In C2 the collimation mirror deflects the optical axis realizing a bent collimator with two axes forming an angle α. Then the concentrating mirror focuses the light on the sensor, introducing a second deflection of the optical axis. The crucial bend is the first one since it affects the quality of the collimated beam with solar divergence. The optical layout of C1 is bent once, but the measured quantity is the entering light, which is filtered (by the mask) in the axial collimator. Then the mirror, bending the optical axis, concentrates the light over the photodetector.

Moreover the use of an integration sphere and the precision in realizing its aperture S represents two other sources of optical errors.

Both collimators generate a series of aberrations that contribute to degrade the definition of the image on the detector. The value of these aberrations must be quantified in order to identify the specific contribution generated by the sample under test. The use of collimator C1 allows limiting the aberrations by an appropriate choice of the Collimation Lens, which should be a lens with field correction and optimized for the used spectral bandwidth. On the other hand, employing collimator C2 the aberrations mainly depend on the collimator angle α and on the surface type of the collimation mirror. In C2 the collimation mirror was chosen to be spherical because it is easy and cheap to be realized. The aberration study was carried out considering a spherical mirror of f_C=1.5 m and an ideal lens with f=250 mm, which represents the component under test. The ideal lens allows analyzing the aberrations of the wave front coming out from the collimation mirror in the position where the solar collectors are usually tested. The aberrations of the beam generated by C2 are reported in Fig. 4 as standard Zernike coefficients C_Z, considering three collimator angles α: 5°, 15° and 25°. The actual angle of the collimator C2 used in our laboratory for collector tests is 15° and the laboratory set-up allows angles up to 23°. The values of spherical aberration, coma, astigmatism and field curvature are plotted versus the entrance pupil diameter of the test lens (in mm), which corresponds to the beam diameter.

The C_Z values plotted in Fig. 4 indicate that the main contribution is represented by the astigmatism and it improves with the diameter of the collimated beam. For beam diameter lower than 150 mm and $\alpha \leq 15°$ the C_Z coefficients are such that the effect of the single aberrations on the quality of the image produced by the lens is negligible. The image maintains high uniformity in intensity.

The degradation of image definition was estimated simulating a collimator C2 with the optical design software Zemax that provided simulations reproducing the profile of the image Sg of our source. The profiles of the image Sg are displayed in Fig. 5a,b for angles α up to 25° and for two beam diameters: 150 mm and 250 mm, corresponding to the total width of the solar divergence beam. For $\alpha \leq 15°$ the image keeps the rectangular shape: hence it can be concluded that our collimator C2 is a very good test system for sample diameters up to 150 mm with $\alpha = 15°$.

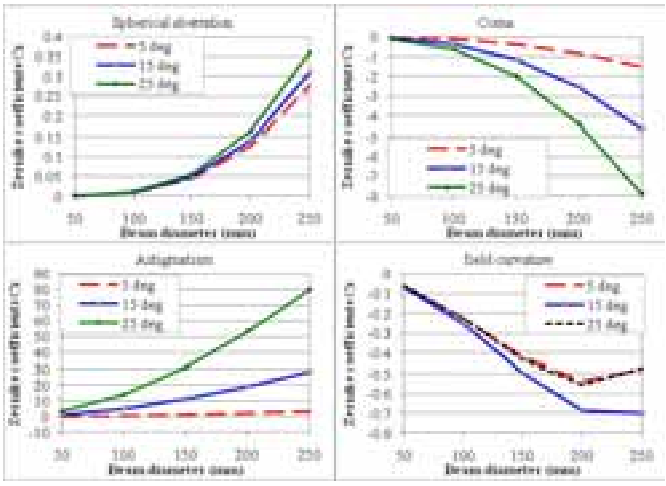

Fig. 4 – Aberrations as Zernike coefficients for α=5°-25°.

As final validation, the reliability of the off-axis collimator C2 to test solar collectors was experimentally verified. This check is reported in Fig. 6 comparing the characteristics of the image produced by an ideal lens, without aberrations, with the image generated by a real solar collector. The comparison of these two optical elements is useful to evaluate the contribution of the aberrations characterizing the off-axis spherical mirror in order to separate them from the contributions due to the tested collector. Figure 6 compares the profile of a real image to the profile of a simulated image. The measured image was acquired by a CCD camera with a Fresnel lens of diameter 180 mm and focal length 195 mm. The simulated curve in Fig. 6 is obtained for a lens with the same optical features, but considered an ideal lens without aberrations. For the real lens the aberrations contribution is visible on the image profile, which results enlarged at the bottom and more smoothed and restricted at the top of the curve. The shape of the ideal lens image is almost rectangular, while the measured image profile approaches a bell shape. It can thus be concluded that for the examined measurements the aberrations of collimator C2 can be considered negligible. It is necessary to repeat this comparison operation at every new collector test in order to verify the degree of interaction of the measurement system with the parameters of the sample to be measured.

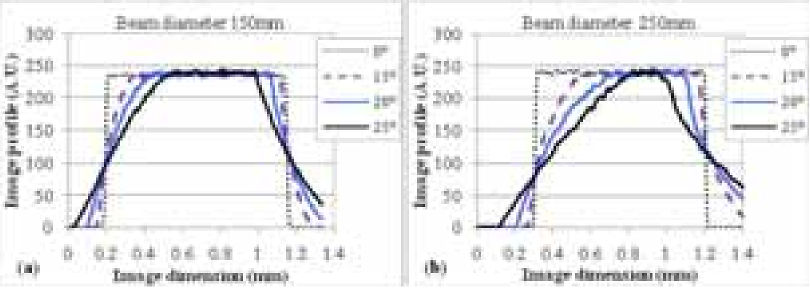

Fig. 5a,b – Image profiles for beam diameter 150mm (a) or 250mm (b).

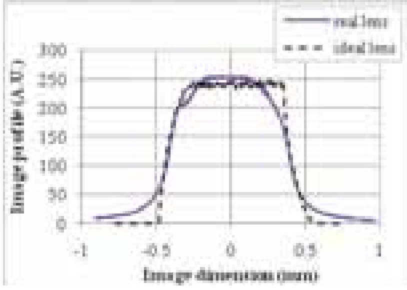

Fig. 6 – Profiles of simulated and detected images.

7 - Measurements of collimated beams

The research is completed by a set of experimental measurements examining the solar divergence beam generated by collimators C1 and C2. The detection is preformed sampling the beam by a photodiode (of side 4 mm) displaced on the vertical plane XY. The sensor is mounted on a motorized translation stage, which is shifted by another translation stage that is perpendicularly mounted. Suitable sampling step and speed were chosen to reach a good trade-off between high definition of acquired image and acceptable length of measurement time. The beam of C1 has diameter 90 mm, hence it can be completely sampled by our detection system, which has a maximum excursion of 150 mm. For C2 the beam has diameter 250 mm, therefore the measurement procedure is more complicated. Two photodiodes are mounted, at a horizontal distance of 150 mm, on the same translation stage and they are displaced together. In this way two parallel sampling are obtained in correspondence of the left and right portion of the beam. To take into account possible differences between the two sensors, the double sampling is repeated exchanging the photodiodes. The final image is then calculated averaging the results of the two measurements.

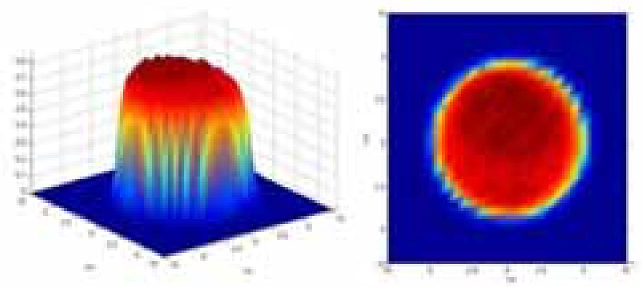

Fig. 7 – Measurement of the C1 beam: 3D and 2D plots.

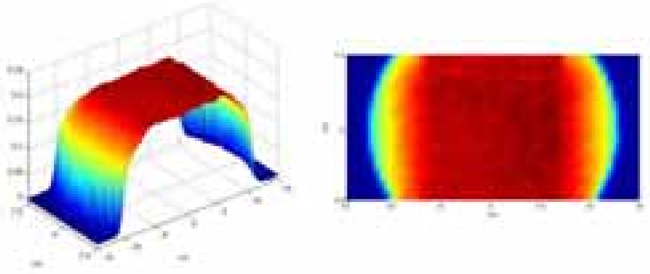

Fig. 8 – Measured C2 beam for α=15°: 3D and 2D plots.

Figure 7 shows the solar divergence beam measured on collimator C1: a 3D plot on the left and 2D image on the right. Analogously Fig. 8 presents the 2D and 3D plots of the measurements on the beam of collimator C2. In the C2 measurements the vertical sampling range is 150 mm while the beam diameter is 250 mm, so the images represent only the central portion of the beam. Nevertheless the sampling is sufficient to contain the beam in the horizontal direction and the aberrations affect this central band of the solar divergence beam. By a practical point of view, in our laboratory set-up C2 the minimum collimator angle α is 15°. This is the value usually employed for the solar component tests, because it minimizes the aberration effects. The beam in Fig. 8 does not show aberration effects, which result to be lower than the detection sensitivity.

It can be concluded that both collimators are appropriate to test solar components: the optical quality of the solar divergence beams is very high for C1 and high for C2. For collimator C1 inside the diameter of 90 mm the beam maintains very high uniformity in intensity with profile variations within 10% of the maximum value. For the beam of collimator C2, the data fluctuations are lower than 10% in the diameter 180 mm and lower than 20% in the diameter 210 mm. Consequently the maximum useful diameter for accurate measurements on the beam obtained with C2 can be considered 210 mm, while high accuracy measurements should be performed within the diameter of 180 mm.

Two aspects can be improved in the described optical systems that reproduce the solar divergence. The first aspect concerns the precise value chosen for the beam divergence: the solar divergence, as total angular aperture, ranges from 0.5253° (Aphelion) to 0.5421° (Perihelion). The second aspect is the reproduction of the solar spectrum, typically performed using halogen or Xenon lamps. Moreover in laboratory we use an optical fiber that selects almost the visible light (350 nm – 800 nm), which is typically the range of use and test of solar components.

8 - Conclusions

Solar concentrators have been studied and experimented within our researches on renewable energies. Our laboratory has developed fiber-coupled collectors, CPV systems and optical systems coupled to various devices. These sunlight concentrators are designed to be applied in thermal sector, internal illumination or photovoltaic field. Optical test and experimentation are a crucial aspect of the development of sunlight components. Some tests compare the measured values of optical characteristics to the nominal values simulated in the optical project. Other optical measurements verify the homogeneity of collector production, comparing the optical features among the different samples corresponding to the same optical project. Our laboratory has developed measurement configurations and procedures to characterize concentrators of reduced size (max diameter/diagonal 240 mm). The solar collectors under test can have various shape, dimensions and collection characteristics. Consequently each image presents different light levels and uniformity features, which require the use of suitable hardware and procedures. Optical instruments, configurations and methodology have been discussed considering the point of view of the researcher realizing the measurements. The described optical tests allow determining image plane analysis, angle dependence, collection efficiency and image dimensions. All these features and behaviors are important to characterize an optical component for sunlight exploitation. Nevertheless each solar application requires adapting the tests to examine the relevant aspects and quantities.

To replicate the working conditions of a direct exposition to the sun, collimators with solar divergence are employed in the optical systems to test solar components. The solar divergence is reproduced combining the output diameter of an integrating sphere to the focal distance of a collimation lens. The solar divergence collimator can be realized in axis for small collectors. While collectors with diameter/diagonal > 80 mm are tested using two large spherical mirrors with focal length 1.5 m. In this case the collimation mirror deflects the optical axis realizing a bent collimator with two axes forming an angle α. This bent configuration introduces some optical errors on the collimated beam with solar divergence. In the bent collimator the beam aberrations depend on the angle α. Measurements of the solar divergence beams have evidenced that both collimators are appropriate to test solar components. The collimated beams do not show aberration effects that are lower than the detection sensitivity. The optical quality of the solar divergence beam is very high for the unbent collimator and high for bent collimator. Besides high accuracy measurements can be performed in the central part of the beam of the bent collimator.

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