INFLUENCE OF CLOUDS AND AEROSOLS TO THE HAZE OF THE SUNSHAPE

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Abstract

The CSR is the thin aureole around the sunshape and results from the forward scattering of direct sunlight by atmospheric aerosols, such as dust, water droplets or ice crystals present e.g. in slight clouds. Solar energy concentrating systems typically collect the direct solar radiation originating from the disk of the sun and a fraction of the CSR. With increasing scattering influence the maximum possible concentration is reduced. This depends on several factors, but knowledge of the CSR can help in predicting or evaluating the efficiency and overall performance of solar concentrating systems.

Ongoing studies at the SIJ provide measurements and analyses of the circumsolar radiation (CSR) for applications and theoretical simulations concerning concentrating solar energy systems. The aim of this research is in the first step the realization of an online measurement and analysis routine of the CSR. With a special digital camera system it is possible to obtain visual measurements of the CSR and a radiation intensity profile of the sunshape. In further steps the results of a ceilometer and a light-scattering spectrometer for particle detecting will be implemented. The combination of the aerosol and cloud data will be analyzed. This helps to understand their influence on the appearance of the CSR and to complete the theoretical description of this occurrence.

Keywords: CSR, circum solar radiation, energy meteorology, concentrating solar energy systems, solar power plants, aerosol, cloud

1. Introduction

Recent studies to examine various options for new meteorological techniques with aim to increase the efficiency of solar thermal power plants have been conducted at the Solar-Institut Juelich (SIJ). These analysis techniques and methods are part of the new discipline - the energy meteorology. Despite new satellite-based measurement methods for weather and climate analysis (for example by EUMETSAT), it is nowadays still necessary that numerous local values are measured locally at the ground because no certain forecast is available. This applies also to various solar irradiation values. For highly concentrating solar thermal plants (100 to 10,000 times sunlight) the direct radiation measured at all times as well as the haze of the solar disk, are a criterion for the quality of the produced focus and the solar efficiency of the plant [1]. In particular the radiance distribution deteriorates in high gain of turbidity. This haze can be quantified with the apparent light increase of the solar disk measured as a grow of diffusing rate from the ground, as the still highly discrete boundary area of the disk above the atmosphere gets blurred more and more by passing through the atmosphere. This increasing aureole around the sunshape is called circumsolar radiation (CSR). Previous studies by [1, 2, 3] have shown that the behavior of the CSR can only partly be explained with the measured values of the direct radiation and seems to depend also on local criteria.

In order to analyze this effect in detail SIJ is currently carrying out automated photo-optical measurements with an analysis of the CSR display at ground level. The calculated values are compared with data from a laser ceilometer and a light scattering spectrometer for local, continuous dust quantification.

2. Background

2.1. Solarthermal Tower Power Plant

In solar tower power plants (see Fig. 1) direct solar radiation is concentrated on top of the solar tower on an absorbing field - called receiver. To realize the necessary concentrating radiation of about 1000 suns, the reflected sunlight is bundled by a high number (several 100 up to several 1000) of large mirrors (10-180 m²), which are tracked to the sun 2-dimensional. Such a kind of mirror system fixed on a stand and tracking by zenith and azimuth is called heliostat.

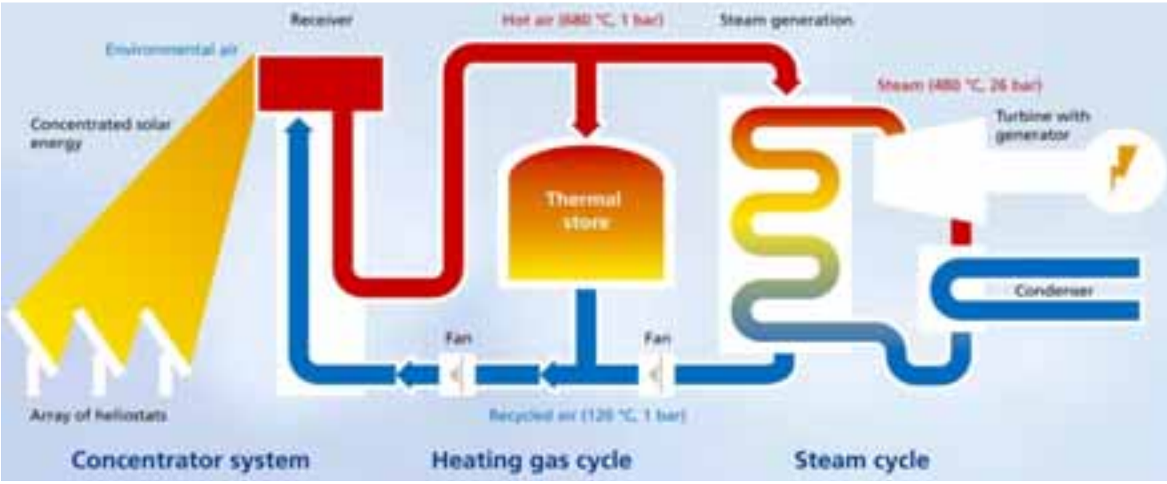

Fig. 1. Layout of the solar tower power plant in Juelich.

This highly concentrated solar radiation heats the absorber area and by the way inside or around the absorber a transfer medium up to high temperatures. This medium can be for example air, water, water steam or oil. Depending on the type of construction of the absorber, temperature values are obtained from 200 °C to 1000 °C. The generated heat is transfer to a steam boiler and on this way used in a steam turbine for conventional generation of electricity.

Fig. 2. Solar tower power plant in Juelich.

Germany’s first and only solar tower power plant for experimental and demonstration purposes is located in the town of Jülich. The central receiver system (CRS), which has been designed with an open volumetric receiver, will supply the grid with a nominal power of 1.5 MWel.

Circum Solar Radiation (CSR)

The visual solar diameter as seen from Earth depends on the position of the elliptic path of the Earth. During the year the distance between Sun and Earth is changing. Thus the solar aperture angle is varying between Perihelion (±4.584 mrad) and Aphelion (±4.742 mrad) by around 3% (Fig. 1) and reaches an average aperture angle of ±4.65 mrad or ±0,266° [4].

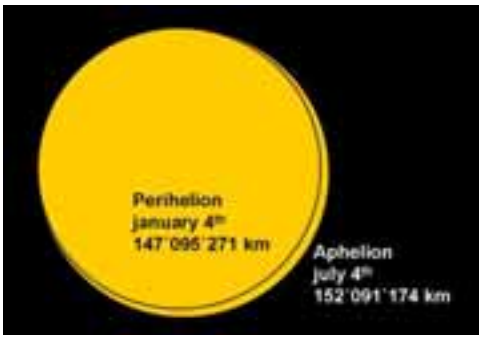

Fig. 1. Difference of the visual sunshape diameter between perihelion and aphelion.

The intensity of the radiation is not homogeneously distributed across the shape because the solar photosphere causes absorption and scattering effects. At the sunshape limb the emitted radiation has a reduced intensity of around 2.5 times to the central maximum.

The flux density distribution of the Sun or rather the sunshape $L_S(\alpha_S)$ can be expressed by [5], [6]

$$L_S(\alpha_S) = b \cdot \left(1 - 0.5138 \cdot \left(\frac{\alpha_S}{4.65 mrad}\right)^4\right) \qquad \text{(eq. 1)}$$

The Factor b is defined differently if one considers a point (2D) or line (1D) focus systems and is given by:

$$b_{1D} = \frac{I_b}{8.959 \cdot 10^{-6}} \, {}^{1}\!/_{sr} \qquad \text{(eq. 1a)}$$

$$b_{2D} = \frac{I_b}{8.344 \cdot 10^{-3}} \, {}^{1}\!/_{rad} \qquad \text{(eq. 1b)}$$

with the direct solar radiation I_b

In the atmosphere, the solar radiation is again deflected by various scattering effects such as Mie or Rayleigh scattering. The optical sharpness of the sun at the ground is reduced by these effects. The circumsolar radiation (CSR) characterizes the ground-level reading of the expanded solar disk diameter caused by the atmosphere and is used to characterize the homogeneity radiation of the sunshape.

The dominating effect is the forward scattering (Mie, 1906) which occurs when the size of particulates existing in the Earth's atmosphere is large in comparison to that of the wavelength of the propagating light. The solar beam is then broadened due to its interaction with atmospheric particulates.

The amount and character of the circumsolar radiation vary widely with geographic location, climate, season, time of day, and the observed wavelength.

If I_{Sun} represents the integrated brightness or intensity of the solar disk and I_{CSR} the integrated intensity of the aureole around the Sun (the circumsolar field), then the CSR value is defined by the ratio [7]:

$$CSR = \frac{I_{CSR}}{I_{CSR} + I_{Sun}} \qquad \text{(eq. 2)}$$

With the part of the radial sunshape

$$I_{Sun} = \int_0^{r_{Sun}} \int_0^{360} \phi(r, \varphi) d\varphi dr \qquad \text{(eq. 3)}$$

And the part beyond the sunshape limb

$$I_{CSR} = \int_{r_{Sun}}^{\infty} \int_0^{360} \phi(r, \varphi) d\varphi dr \qquad \text{(eq. 4)}$$

As obtained from optical measurements CSR values range typically from a few percent to values even up to 40% [7].

2.2. Effects and Consequences

The energy transfer from the sunshape area into the circumsolar region has two main consequences. On the one side because of the increase of the diffuse radiation part this can lead to an over estimation of the energy collected in a solar concentrating system. And on the other side, it alters the beam width of the flux distribution in the focal plane of the concentrator.

Under some circumstances these aerosols can cause a significant fraction of the solar flux to be deviated to angles of several degrees or more. Solar energy conversion techniques using high concentration ratios, such as solar central receivers and parabolic dishes, only collect light from the solar disk and a small portion of the circumsolar region [1].

The solar energy system will typically collect all of the direct solar radiation originating only from the disk of the sun plus some fraction of the circumsolar radiation. The exact fraction depends on many factors, but primarily on the receiver’s angular size (its field-of-view).

As typical pyrheliometers integrate the radiation of an angle of 5° to 6° with the sunshape in the center, they do not only measure the direct solar radiation, but their measurements include a large portion of the circumsolar radiation. Thus the amount of direct sunlight that would be collected by a solar concentrating system is overestimated.

2.3. Aerosols and Clouds

The occurring CSR depends on the existing scattering targets in the atmosphere and the corresponding hit probability. The statistic includes the appearance of the different aerosols and special thin clouds.

In particular the lower troposphere between ground and an altitude up to around 1000 m is much more contaminated by solid aerosols than the upper 14 km. Following this fact means, that especially the near ground region could have a high count of sun light scattering effects. These kinds of aerosols can be distinguished by source depending on nature or human influence.

- anthropogenic sources: industry, traffic, agriculture, different kinds of urban pollution, etc.
- natural sources: inorganic geological particles (see salt, sand, dry soil, volcanic ash, etc.) and biological phenomena (light seeds, pollen, spurs, microorganism, ash of forest fire, etc.)

Another option is to characterize the particles by size or weight. Here the range includes the large scaled grid down to the ultra fine particle.

The kind of clouds which have a remarkable influence on the CSR must be very thin. If they reach a certain thickness the optical density is blocking the direct radiation too much and the sunshape is not or only very poorly visible behind the cloud. Because of that the most important category of clouds is on the one side cirrus - in all small variations in the high troposphere – and on the other hand the category of thin nebulous dust in the middle or deeper troposphere.

3. Measurements

3.1 Insitu Photo Optical Measurement of CSR

A high resolution digital camera provided with a telephoto lens and special solar filter is mounted on a solar tracker and used to take and store actual shots of the visual sun. The images of the sun usually show an excellent circular symmetry. Therefore for the calculation of the CSR it is sufficient to integrate the brightness distribution of the sun only along the radial coordinate. On this way these photo data are processed and can be analyzed insitu. Thereby especially the decreasing intensity values near the sunshape outer limit are of interest (Fig. 2).

With the additional data of a pyrheliometer mounted parallel to the camera, the radiation distribution can be calibrated. This offers investigators of test facilities with concentrating solar radiation a chronological profile of the CSR for further analysis.

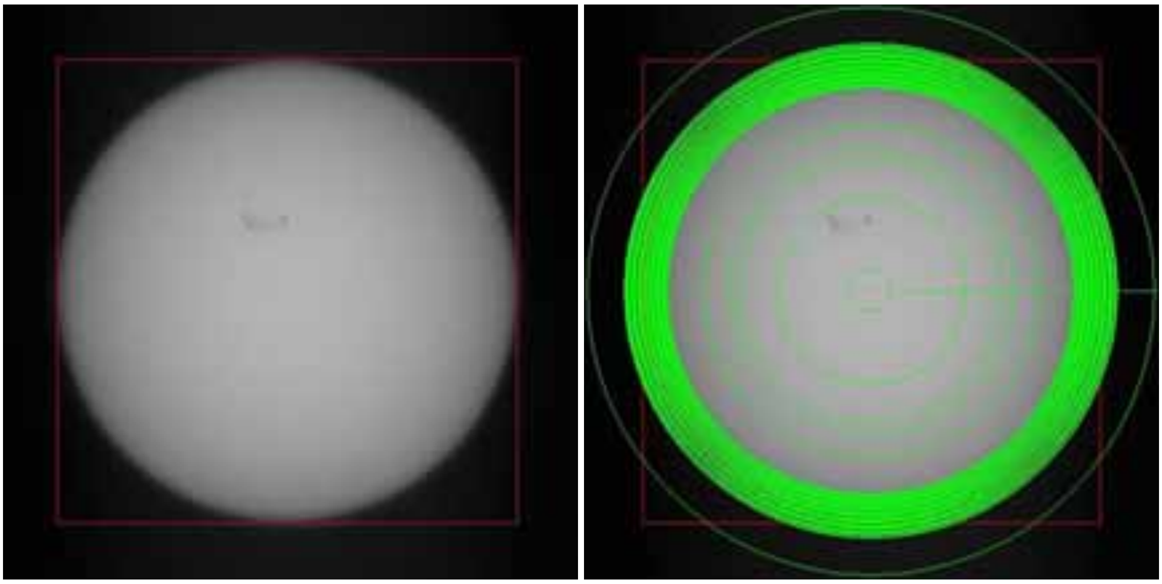

Fig. 2. Digital photo of the Sun (10.03.2011 10:30 in Juelich, left) is analyzed by a program realised by LabView Vision Builder (right side). By splitting radial sections the program observes the radial intensity decrease of the radiation beneath the astronomic limb.

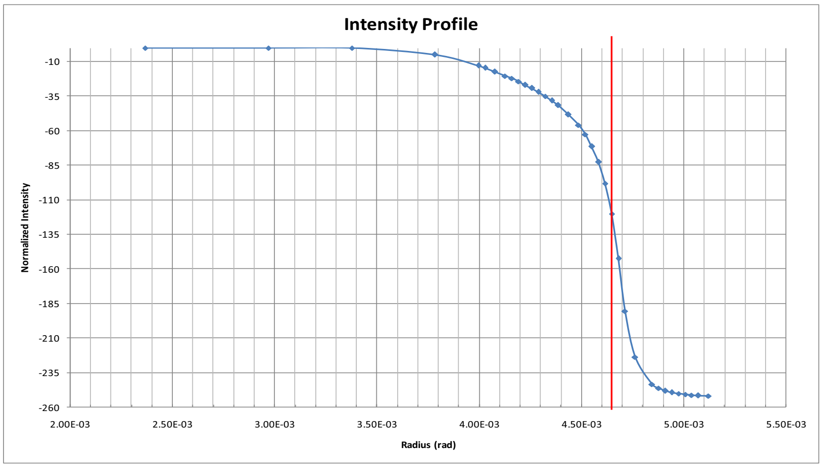

Fig. 3. Radial intensity decrease of the sunshape caused by scattering effects and the resulting CSR.

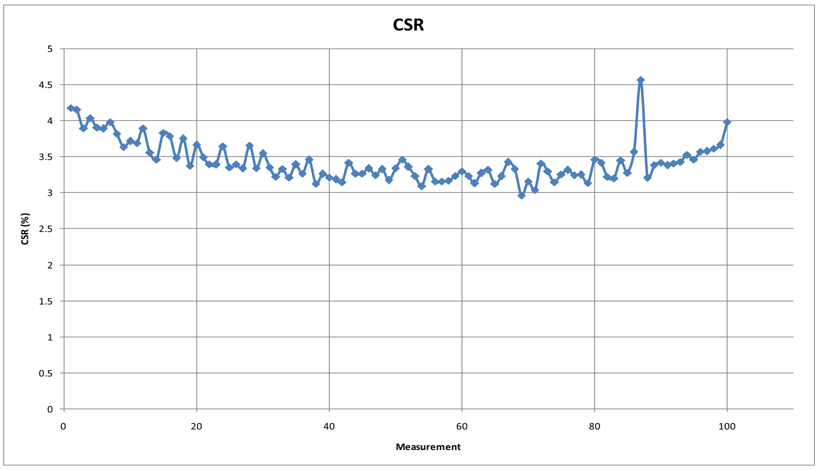

Fig. 4. Temporal validation of the CSR value during a lapse of a measurement campaign

3.1 Insitu Measurement of Aerosol and Cloud Conditions

The actual data of the aerosol and cloud conditions are necessary for the next step in the development plan. A good combination to find out the essential characteristic values can be the use of a high reaching ceilometer and a downside measuring light scattering spectrometer.

The ceilometer (Fig. 5) offers aerosol and cloud values across the troposphere (Fig. 7) and the light scattering spectrometer (Fig. 6) measures the ground near dust situation (Fig. 8).

Fig. 5. Ceilometer unit

Fig. 6. Boxed light scattering spectrometer combined with a small meteorological station

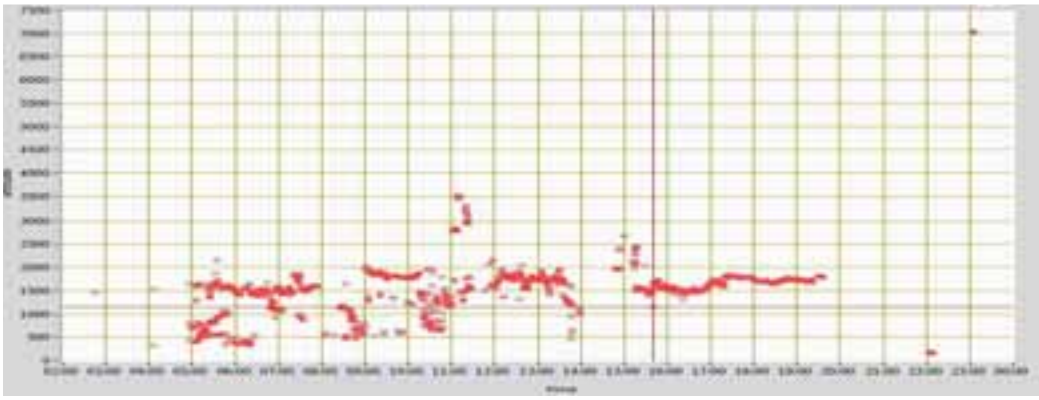

Fig. 7. Temporal validation of clouds and aerosols (Data analyzer laser ceilometer)

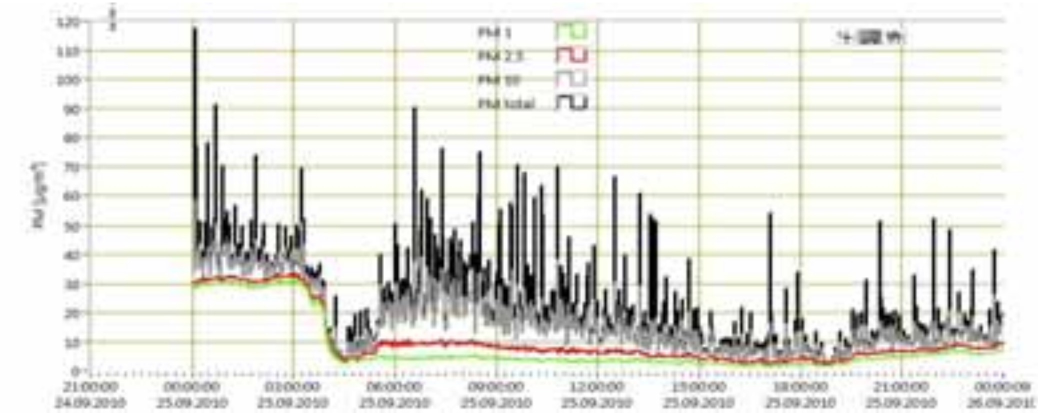

Fig. 8. Temporal validation of the local atmospheric particulate matter by pm-standard (Data analyzer light scattering spectrometer)

4. Conclusion and Further Steps

SIJ carries out research and develop projects about solar concentrating systems and other domains of energy engineering. The influence of CSR on highly concentrating systems is now investigated in several steps. In the beginning an insitu measuring photo optical system was realized to detect the value of CSR.

Goal of the ongoing research is to analyze the criteria of the origination of CSR over the previous optical measurements by analyzing the aerosol and cloud components of the atmosphere and stratosphere. Meantime two established aerosol measurement device been installed for this investigations and are being calibrated at the moment: A ceilometer to measure cloud and aerosol layers and a light scattering spectrometer for quantification ground-level, continuous dust.

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