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APPLICATION OF CIRCUMSOLAR MEASUREMENTS TO CONCENTRATING COLLECTORS

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ABSTRACT

A systematic measurement program is being carried out to assess the effects of circumsolar radiation (the solar aureole) on the performance of solar conversion systems using concentrating collectors. Four instrument systems have been constructed and are providing detailed intensity vs. angle profiles of the solar and circumsolar (out to 3^{o} from the center of the sun) as well as other solar measurements. The instruments are briefly described. Results are presented of the average effect of the circumsolar radiation on the solar energy available to an idealized point focusing system. Results are also presented for an analysis of two specific Central Receiver designs.

1. INTRODUCTION

Circumsolar radiation (or the solar aureole) is caused by the forward scattering of direct sunlight by atmospheric aerosols. The aerosols include dust, particulates from air pollution, and ice crystals or water droplets in thin clouds. To an observer, or to a solar energy system that uses lenses or mirrors to concentrate the solar radiation, this scattered light appears to originate from the region around the sun.

Concentrating solar energy systems typically collect the direct solar radiation (that originating from the disc of the sun) plus some fraction of the circumsolar radiation. The exact fraction depends upon many factors, but primarily upon the angular size (field-of-view) of the receiver. A relatively larger receiver will collect more of the circumsolar radiation, but may well experience relatively larger radiative and convective losses. A knowledge of the circumsolar radiation can be used as a factor in the optimization of a receiver design, as one measure of the suitability of a geographic region for concentrating systems, or as input to comparison studies of competing designs at a particular location.

Pyrheliometers measure a substantial fraction of the circumsolar radiation, as well as the direct solar flux, and thus to some extent overestimate the amount of energy available to a highly concentrating system. Similarly, pyrheliometer measurements will underestimate the energy available to systems of low concentration.

2. INSTRUMENTS

Four instrument systems known as "circumsolar telescopes" have been constructed. Details of the instruments are given elsewhere (1). Briefly, a precision solar tracker keeps a reference platform pointed at the center of the sun. A specially designed telescope is mounted on the platform and mechanically scanned thru a 6^{o} arc with the sun at the center. Each scan takes one minute of time; a digitization of the brightness of the sun or circumsolar region is made every 1.5 minutes of arc. The detector is a pyroelectric crystal - a type of thermal detector. The basic measurement is then relatively wavelength insensitive, as are most current receiver designs for thermal conversion. In addition to this basic measurement, scans are made thru eight colored filters that divide the solar spectrum into eight bands of roughly equal energy content. These filtered measurements are applicable to concentrating photovoltaic systems, or to thermal conversion systems employing selective surfaces. The work reported here will only consider the unfiltered data.

A pyrheliometer of the Active Cavity Radiometer type (2) is mounted on the reference platform and provides the calibration for the telescope scan as well as the usual normal incidence reading. The telescopes are designed to provide data for all weather conditions during which concentrating solar energy systems would be operating. The instruments can function unattended for periods of up to a week, although a daily check is usually made.

Telescopes are currently operating at the Central Receiver Test Facility at Albuquerque, New Mexico; the Advanced Components Test Facility at Atlanta, Georgia; and near the site of the Central Receiver Pilot Plant at Barstow, California. Data have also been taken at Ft. Hood, Texas, China Lake, California and Argonne, Illinois.

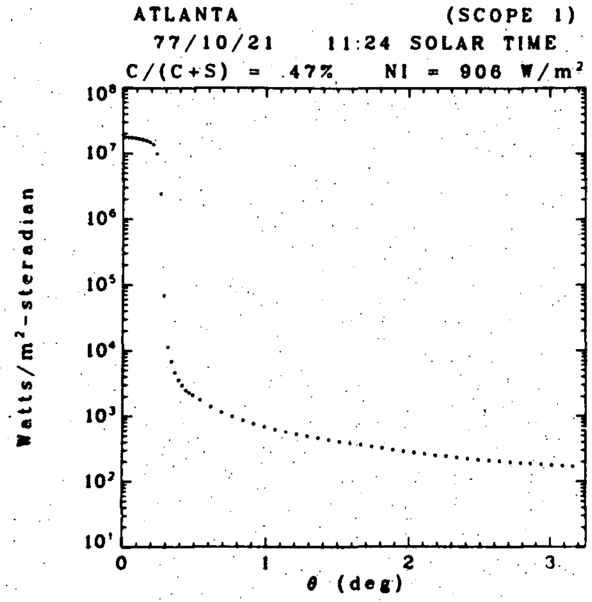

Fig. 1. Example of telescope measurement for clear skies.

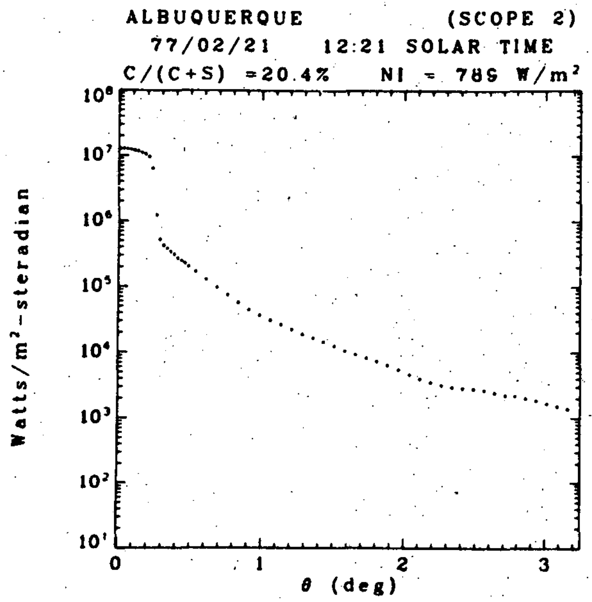

Fig. 2. Example of a measurement for hazy skies.

3. EXAMPLES OF MEASUREMENTS

Examples of scans of the telescope are shown in Figs. 1 and 2. As displayed here, the scans are from the center of the sun out to about 3^o. (Thus essentially half of the original 6^o scan is shown.) Fig. 1 is for clear skies, and Fig. 2 for a day with haze or thin clouds. It is seen that for the hazy day the circumsolar level is considerably higher, both in energy units and relative to the brightness of the sun. The direct solar radiation (S) is taken as the integral from the center of the sun out to one solar radius, and the circumsolar radiation (C) as the integral from the solar radius out to the end of the scan. C/(C+S), the "circumsolar ratio", is then taken as a measure of the circumsolar radiation. This ratio is given on Figs. 1 and 2. The NI = in the figures refers to the Normal Incidence reading of the pyrheliometer. Because the 6^o scan of the telescope approximately matches the field-of-views of typical pyrheliometers, the circumsolar ratio is an approximate measure of the error made by a pyrheliometer in measuring the direct solar radiation. As indicated by Figure 1, there are clear sky conditions for which the pyrheliometer error is less than 1%. For such conditions, the circumsolar radiation is of negligible importance for concentrating systems. However, as indicated by Fig. 2, there are sky conditions for which the circumsolar ratio can be as much as tens of percent for moderately high normal incidence values. For such conditions, the pyrheliometer would significantly overestimate the amount of energy available to a concentrating system with a relatively narrow field of view.

4. APPLICATION TO IDEALIZED POINT FOCUSING SYSTEM

To assess the overall effect of the circumsolar radiation on concentrating solar energy systems, all sky conditions during which the system would be operating must be taken into account. In order to accomplish this in a parametric way, an idealized point focusing system has been defined in terms of two simplified parameters. This first is an operating threshold. Whenever the normal incidence (NI) reading of a pyrheliometer is above this threshold (NI_t) the solar plant is considered to be in operation. The second parameter refers to the angular acceptance of the receiver. We define an effective aperture radius (half the field-of-view) in angular units measured from the center of the sun. All solar and circumsolar radiation within this angle are incident upon the receiver; all light outside this angle "misses" the receiver.

Let $B(\theta)$ be the brightness of a given scan of the telescope (as in Fig. 1), θ_e the effective aperture radius, and NI_t the operating threshold. Then the power (watts/meter squared) available to the idealized power plant will be

$$P = \int_0^{\theta_e} B(\theta)d \quad , \qquad NI > NI_t$$
$$P = 0, \qquad NI < NI_t \qquad (1)$$

Next, the contributions from the various scans made over the course of a month are summed. For any given month, there are often gaps in the data due to instrumental difficulties. These gaps are almost always uncorrelated with weather conditions; the loss of data then represents a decrease in the statistical significance of the results rather than a bias. Months with less than a week's worth of data are rejected. For acceptable months the approach is as follows: The day is divided into K intervals of solar time of length H hours each. For a given time interval (k) the average power available for the month is

$$P_k = \left[\sum_{i=1}^{N_k} P_i\right]/N_k$$

where the sum is over the N_k scans within the time interval. The average daily energy content in each interval is just

$$E_k = P_k \cdot H$$

and the average daily energy available for the month is

$$E = \sum_{k=1}^{K} E_k \qquad (2)$$

In practice, H is taken to be one hour, and E is calculated for a variety of thresholds and effective aperture radii. For present purposes, these values of E are not displayed directly, but rather the results for various effective radii are compared to a reference value. This value is taken as the total solar plus circumsolar radiation as measured by the telescopes, which corresponds to equation (2) for an effective aperture radius of 3.2°. As compared to this reference value, there is a reduction in the energy available to idealized solar systems with an effective aperture radius less than 3.2°. Let E_r be the reference value and E_e be the value for an arbitrary effective radius. A fractional energy loss, F_e, is then defined,

$$F_e = (E_r - E_e)/E_r$$

Figures 3 and 4 show the energy loss for about a year's worth of data at Barstow and at Atlanta, respectively. In these figures, the effective aperture radius of 0.28° essentially corresponds to the radius of the sun. For purposes of discussion, consider the curve for 0.38°. The loss for Barstow ranges from a low of 2% in June of 1978 to a high of about 6% in January of that year. As a cautionary note, it should be mentioned that the winter months for 1977-78 were particularly cloudy and the values may not be representative of average conditions.

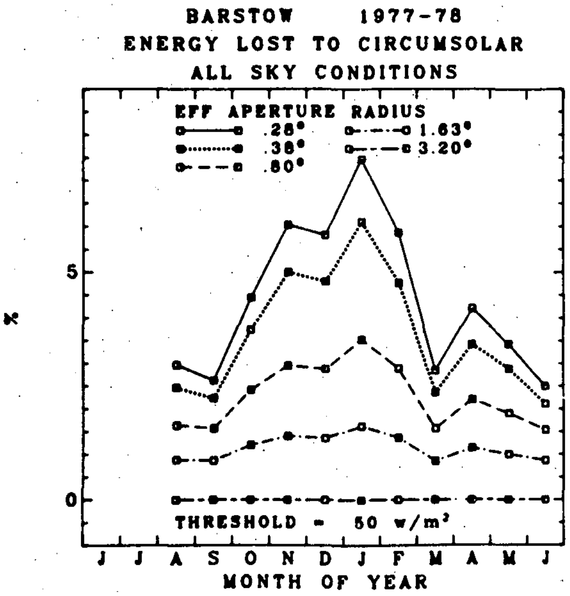

Fig. 3. Energy loss for various effective aperture radii for Barstow, California for the period August, 1977 thru June, 1978

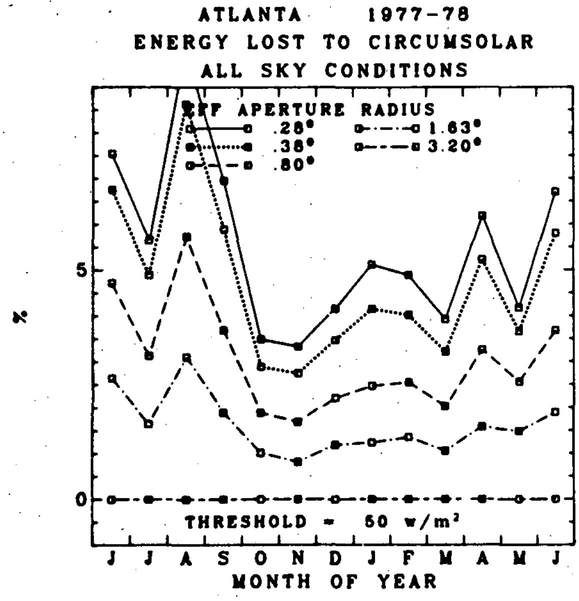

Fig. 4. Energy loss for Atlanta, Georgia for the period June, 1977 thru June, 1978.

For Atlanta, the loss ranges from a low of about 3% in the fall of 1977 to a high of about 8% for August of that year. Although the losses for Atlanta (a relatively humid climate) are higher than for Barstow (a semi-arid area), the differences are not dramatic. It should be noted that Figures 3 and 4 do not give the total energy available at Barstow as compared to Atlanta. This total is significantly higher for Barstow than for Atlanta.

As discussed above, the telescope scan roughly covers the field-of-view of typical pyrheliometers. Correspondingly, the value E_r approximates the normal incidence reading of this latter instrument. Figures 3 and 4 may then be taken as an indication of the extent to which a pyrheliometer would overestimate the amount of energy available to various sized receivers.

5. APPLICATION TO CENTRAL RECEIVER DESIGNS

Actual concentrating solar energy systems are considerably more complicated optically than the idealized system considered above. For central receiver power plants, each heliostat has a unique geometrical relationship to the receiver. In addition mirror surface irregularities, tracking errors, and shading and blocking of one heliostat by another must be taken into account. Computer simulation programs are necessary to study the optical characteristics of such systems. Addressed in this section is the energy lost (in the sense of section 4) to two specific conceptual designs for the 10 Megawatt-electric pilot plant to be built at Barstow. The designs are those of Martin-Marietta, and of McDonnell Douglas (3). The analysis is based on computer simulations made by Sandia Laboratories, Livermore (4).

In principle, the simulation program could be used to calculate the energy loss of (or, conversely, the energy available to) a specific design for each measurement of the telescope, as was done using equation (1) for the idealized system. In practice, the computer time that would be needed rules out such an approach. Instead, 16 solar plus circumsolar profiles (of the type shown in Figs. 1 and 2) were selected to cover a wide range of behavior of the circumsolar radiation. For each of these "standard profiles" (and for the two designs) MIRVAL was used to calculate the fraction of the energy content of each profile that was lost to (missed) the receiver. Any given telescope scan was then matched in shape (but not magnitude) to the standard profiles using a chi-squared test. Let R_n be the circumsolar ratio (see section 3) for telescope scan "n", F_s be the fractional energy loss for the standard profile "s" that best matched the scan, and R_s be the circumsolar ratio for that same profile. We then define the fractional loss for the scan to be

$$F_n = F_s \cdot (R_n/R_s)$$

This definition partially takes into account the fact that any given measurement will differ in shape somewhat from the best matched standard scan.

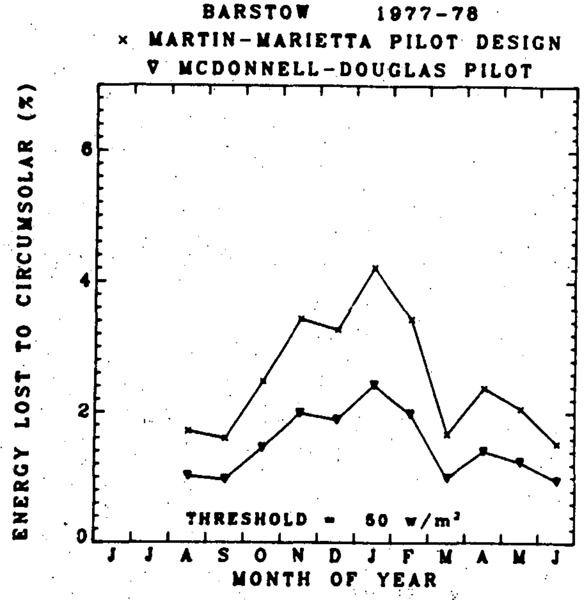

Fig. 5. Energy loss for two central receiver designs for data taken at Barstow.

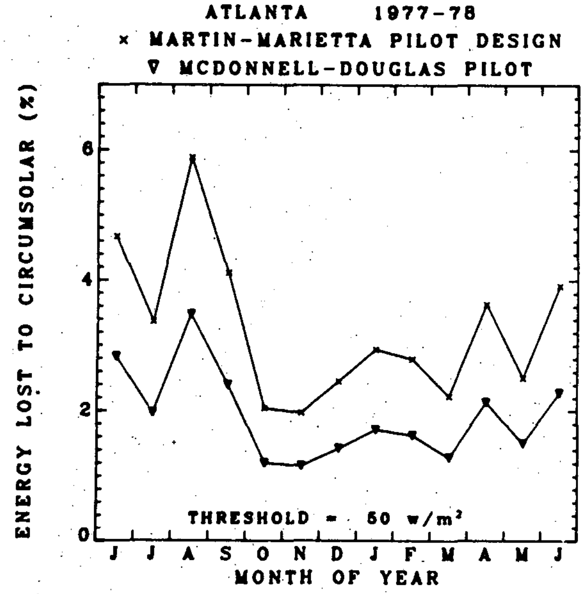

Fig. 6. Energy loss for two central receiver designs for data taken at Atlanta.

Once F_n is determined for each scan, the procedure is similar to that outlined in the previous section. Now, however, the calculation is made for each of the two designs rather than for various effective aperture radii. The results are displayed in Figs. 5 and 6 for the same locations and periods of time as for Figs. 3 and 4. For the McDonnell Douglas design (an open receiver) the loss ranges from a low of about 1% (summer months at Barstow, and October and November at Atlanta) to a high of about 3.5% for August at Atlanta. For the Martin Marietta design (a horizontal cavity) the range is from about 2% to 6%.

A comparison of Figs. 5 and 6 to 3 and 4 show that the month-to-month variation for the actual designs are similiar to those for the idealized system. In particular, the Martin Marietta design corresponds, roughly, to an effective aperture between 0.38^o and 0.8^o, and the McDonnell Douglas design to an aperture between 0.8^o and 1.63^o.

6. DISCUSSION OF RESULTS

The above analysis has estimated the energy lost to circumsolar radiation both for an idealized point focusing system and for two specific central receiver designs. This "loss" may also be taken as an indication of the extent to which an ordinary pyrheliometer would overestimate the solar energy available to such plants. For Barstow, California, a semi-arid area with generally clear skies, the monthly average loss ranges from a low of 1% to a high of about 6%, depending upon the time of the year and the angular size of the receiver. For Atlanta, the range is from about 1% to 8%. These values are comparable to other energy loss mechanisms associated with concentrating solar energy systems (3). Thus the circumsolar radiation should be taken into account, along with these other factors, when the overall performance of a concentrating system is investigated.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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(3) "Recommendations for the Conceptual Design of the Barstow, California, Solar Central Receiver Pilot Plant - Executive Summary," Sandia Laboratories report No. SAND77-8035, October 1977.

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