AN OPTICAL SYSTEM FOR THE QUANTITATIVE STUDY OF PARTICULATE CONTAMINATION ON SOLAR COLLECTOR SURFACES

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Abstract—We describe a computerized microscope system that has been developed for studying the physics of dust particles which adhere to various kinds of surfaces such as those of solar collectors. The device enables investigators: (1) to obtain the particle size distribution of dust on a surface; (2) to calculate the fraction of surface area covered by dust; (3) to calculate the reduction of optical efficiency (of the solar collector under study) as a function of particle size; (4) to investigate the effect of various kinds of applied force field on the adhesion of dust particles to the surface. Some examples are given for the use of such a measuring system for the study of photovoltaic and solar-thermal collector surfaces. © 1999 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The contamination of solar collector surfaces by dust can be a source of considerable loss of revenue for a solar power station. For example, a solar collector surface that is maintained at a cleanliness level of 90% relative to a perfectly clean surface will, for many kinds of collectors, imply an annual loss in revenue of 10%. Furthermore, washing with water – the conventional manner in which solar collector surfaces are cleaned – may well involve prohibitive costs in those regions, namely deserts, where solar power plants are likely to make their greatest societal impact, both as regards to efficiency and practicality.

Clearly, even if water (albeit scarce) is available for cleaning purposes, one would like to be able to make a quantitative study of the dust soiling rate in order to minimize the use of cleaning water. On the other hand, if water is not available one would like to be able to study the physical properties of dust on the collector surface in order to be able to develop dry-cleaning methods as alternatives to water.

The general problems of collector surface maintenance have been reviewed in the books by Rabl (1985) and Stine and Harrigan (1985). The optical effects of small particles of various sizes have been discussed in the book by Van de Hulst (1957) and in a number of papers, for example, that by Young (1976). Typical sizes of particles in the atmosphere have been discussed by Pye (1989) and systematic measurements of the deposition velocities and fluxes of particles of various sizes have been reported by Lin et al. (1994).

Recently, the influence of particulate contamination on the output of photovoltaic cells has been studied by El-Shobokshy and Hussein (1993) and, on the performance of evacuated tube collectors, by El-Nashar (1994).

The major conclusion that can be drawn from a perusal of all studies associated with the problem of contamination by particulate matter is that it is the range in the physical size of the particles which mostly determines the physics appropriate to the solution of each specific problem. In the case of the optical degradation of surfaces, particles of less than 1 micron in size are less important than larger ones. This fact suggests that it should be possible to study the soiling of surfaces by relatively low-cost, optical microscopy.

In this article we describe the features of a computer-based optical microscope we have developed for studies of this kind. The basic principles of image processing in microscopy may be found in the review by Russ (1990).
2. A COMPUTERIZED MICROSCOPE

2.1. Hardware

Since, as mentioned above, the particle sizes of interest exceed the wavelength of visible light, an optical microscope can provide the necessary resolution of the dust particles we wish to study. However, in order to obtain a particle size distribution it is clearly inconvenient to count particles manually and arrange their numbers by size: this needs to be done by a computer. We have accordingly devised a system comprising of an optical microscope, a CCD camera, a frame-grabber, a storage computer and an appropriate image-processing software. The system is illustrated schematically in Fig. 1.

Specifically, we employed a MonoZoom-7 video microscope (Cambridge Instruments Corp.), equipped with a $2 \times$ objective together with $2 \times$ and $3 \times$ amplifiers. This provides magnification in the range of $2 \times - 42 \times$. An additional amplifier provides magnification up to approximately $100 \times$ if needed, but the resultant magnification on a $12''$ monitor screen is 18 times higher.

Under optical magnification of $42 \times$, the CCD array resolution is approximately 0.3 micron per pixel. This provides a working distance, under the objective, of 36 mm or more, rendering it possible to perform experiments on the dust while directly viewing the process under highest magnification. Furthermore, at any desired moment, a ‘snapshot’ may be stored in computer memory for future comparison with another such picture and/or for image processing and numerical data analysis.

The CCD camera is a JE 7442X B/W (Javelin Corp.) whose matrix of pixels has an active area of $756 \times 581$ sensors and physical dimensions of $8.8 \text{ mm} \times 6.6 \text{ mm}$. The 8-bit information in each pixel allows 256 possible grey levels. A DT 2855 frame grabber (Data Translation Corp.) is employed to digitize the analog output signal from the camera. The primary image is first viewed on a B/W video monitor allowing the user to select the field of view, the desired magnification and the appropriate plane of focus. The digitized image is then transferred to computer memory, if desired, for later use. An important feature of the frame grabber is an external trigger that allows synchronization of image capture with pulses from an external signal generator.

2.2. Software

In order to determine the distribution of particles according to their sizes on a given surface of interest, it was necessary to develop a specialized, problem-oriented, computer code. This process involves the following principal stages:

1. Determination of a threshold grey level for background subtraction. This procedure is supported by subroutines which provide the possibility of viewing a brightness histogram (Fig. 2), i.e. a frequency distribution of grey levels, ‘zooming in’ on any desired rectangular region of the frame, viewing the numerical...
value of grey level in any individual pixel and making a contour map of all grey levels which exceed the initially defined threshold.

2. Background subtraction and conversion of the 256 grey level contour map into a black and white binary image.

3. Calculation of an array, in pixels, of $S_j$, the projected areas of all particles in the frame.

4. Conversion of the projected areas into an array of equivalent circle diameters, $d_j$, [microns], using

$$d_j = 2k\frac{\sqrt{S_j}}{\pi}$$  \hspace{1cm} (1)

where $k$ is an empirical scaling factor to microns, obtained by ‘photographing’ any convenient object of known size, e.g. a stage micrometer.

It should be pointed out that $d_j$, as defined in eqn (1), corresponds to the equivalent diameter of a particle on the surface of interest. It is thus suitable for the assessment of optical degradation of such a surface. Special corrections must, however, be applied to $d_j$ for use in other applications. For example, it is often necessary to take into account the fact that most particles are to some extent elongated and tend to settle on a surface so as to have minimum potential energy. This phenomenon makes the average projected area diameter for an ensemble of particles larger than it would be for the same particles if they were randomly oriented. Depending on specific particle and surface properties (e.g. electric charge) this correction, in the most common case, depends on particle shape and, if neglected, can result in substantial errors when calculating mass distributions, volumetric diameters, aerodynamic diameters, etc. In one of our subroutines the corrected volumetric diameter is calculated according to the expression

$$d_j' = 2k\sqrt{\frac{S_j}{\pi(a/b)^{1/6}}}$$  \hspace{1cm} (2)

where $2a$ and $2b$ are respectively the width and length of the elongated particle ($a < b$), the latter being replaced by an ellipsoid of revolution having equal projected area. The derivation of eqn (2) is given in the Appendix.

5. Calculation of a frequency distribution of particles according to their projected area or corresponding projected area diameter.

6. Automated reading of sequences of files in the hard disk and calculation of the corresponding particle size distributions.

7. Creation of final histograms of size distribu-
tions and covered area distributions, showing the percentage surface area obscured by dust particles.

All of the above software was developed to operate within the Windows 3.1 environment of a PC computer.

3. SOME TYPICAL EXAMPLES OF SOLAR APPLICATIONS

3.1. Dust distributions on PV modules

The effect of dust on a PV module is complex. A fine layer may actually improve the daily output of a module by reducing large angle reflections from the cover glass. On the other hand, thick layers of dust on the glass will obviously reduce its transmissivity. Also, industrial soot may be expected to have a different effect than windborne desert sand or agricultural pollen. Clearly then, a computerized microscope of the type described above, which has a large working area beneath its objective lens, will be a valuable research tool for such studies.

Fig. 3 is a picture (actually a video image using a similar camera to the one described) of a PV module under such investigation. The module dimensions are 140 cm x 40 cm x 4 cm. The resulting particle size distribution, shown in Fig. 4, indicates, inter alia, that in this specific situation the total area of glass occupied by dust is 0.47%. Fig. 5 shows the corresponding distribution of particle diameters when the eqn (2) correction is included. It is, perhaps, of passing interest to point out that the corresponding reduction in short circuit current was found to be significantly less than 0.47%. Qualitatively, this indicates that the type of dust present in this specific case does not simply block out the incoming light. A combination of I–V curve data and microscopy of the kind discussed here therefore permits the quantitative evaluation of various models for light scattering by dust on the surface of PV modules.

3.2. The optical degradation of mirror reflectivity

In the case of large collector surfaces, such as the parabolic mirrors of solar-thermal power plants or the V-trough mirrors of certain PV plants, it is necessary to attach small dust-collecting surfaces for known periods of time. These test surfaces, which will subsequently undergo microscopic analysis, must be attached to the main surface with great care, in order to ensure that they cause no disturbance to the natural flow of air.

Fig. 6 shows the result of a typical experiment in which we wanted to study particle size distributions on fixed and tracking surfaces at the same geographical location. In this specific case the flux distributions are compared for a fixed,
horizontal, upward-facing mirror and for an east to west sun-tracking, V-trough mirror. The results indicate that the relative particle size distributions are similar for the two cases but that, for the same period of time, the fixed horizontal mirror accumulated 4 times as much dust as the tracking mirror. By integrating the area under each of the curves in Fig. 6 we find that, in the case of the fixed mirror, 3.98% of the surface area is covered by dust, whereas for the tracking-mirror the corresponding fraction is 0.99%. These results clearly also represent the numerical values for degradation in specular reflectance. It is worthy of mention that measurements performed with a portable specular reflectometer (Model 15R manufactured by Devices & Services Corp.) indicated a value of 4.0 ± 0.1 for the ratio of the corresponding levels of degradation in reflectance. By using this technique for first measuring the reflectance of a soiled surface, cleaning the surface and then remeasuring its reflectance, long-term degradation effects (such as oxidation, etc.) may be monitored. Successive comparison of microscopic images of new and aging reflecting surfaces may help in understanding the main sources of degradation.

3.3. Experiments under the microscope

Another valuable feature of the large working distance between the objective lens and its object plane is that it enables experiments to be performed with various applied force fields and the results to be analyzed in ‘slow motion’. For example, Fig. 7 is a time sequence showing three stages of the deaggregation, under the application of an electric field, of a single, aggregated loess particle. The size of the initial particle was approximately 40 microns. The images in this experiment formed part of a study into possible methods of ‘dry-cleaning’ the mirror surfaces of large solar power plants.

4. CONCLUSIONS

We have described a device for the study of surfaces contaminated by particulate matter which provides information about: (1) the distribution of particles according to their projected area diameters; (2) the distribution of surface area fractions occupied by particles of different sizes; (3) the degree of contamination, via calculation of the fraction of surface area covered by dust.
Fig. 5. Distribution as in Fig. 4 but corrected via eqn (2).

Fig. 6. Comparison of particle flux distributions according to particle sizes, for fixed horizontal and east to west tracking mirror surfaces.
Fig. 7. Example of an *in situ* experiment performed under the computerized microscope: three consecutive stages of the deaggregation in an electric field, of an aggregated loess particle with an initial projected area diameter of 40 microns.
In the case of photovoltaic modules, this tool provides an important, non-invasive method of obtaining data that supplement conventional I–V curve measurement techniques for studying module degradation as in Berman et al. (1995).

In the case of mirror surfaces in solar concentrators the method provides information of a more quantitative nature than that obtainable from a specular reflectometer.

In both situations, the fact that a differential particle distribution is obtained enables a quantitative study of the physics involved in the various dust deposition mechanisms to be undertaken, as in Biryukov (1998). Such physics studies are enhanced by the possibility, as illustrated above, of performing actual experiments on dust while under the microscope.

**APPENDIX**

Consider an ellipsoid of revolution having semi-minor axis \( a \) and semi-major axis \( b \), \((a < b)\). Introduce a shape factor

\[
\eta = \frac{b}{a}
\]

(A1)

The projected area of such an ellipsoid is

\[
S = \pi ab
\]

(A2)

We wish to calculate the equivalent radius of the projected area \( S \), of an ensemble of such particles randomly distributed in 3D space. This radius can be determined as the radius \( r_v \) of a sphere of equal volume to our ellipsoid of revolution

\[
\frac{4}{3} \pi a^2 b = \frac{4}{3} \pi r_v^3
\]

(A3)

From eqns (A2) and (A3) it follows that

\[
r_v = \sqrt[1/6]{\frac{a S}{\pi}}
\]

(A4)

but from eqns (A1) and (A2) we have

\[
a = \sqrt{\frac{S}{\pi \eta}}
\]

(A5)

Hence, from eqns (A1), (A4) and (A5) we obtain

\[
r_v = \left(\frac{S}{\pi (ab)}\right)^{1/6}
\]

(A6)

Since \( 2r_v = d_j \), we see that, up to the scaling factor \( k \), eqn (A6) is equivalent to eqn (2) in the text.

**REFERENCES**


