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Airborne Sand and Dust Soiling of Solar Collecting Mirrors

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Abstract. The reflectance of solar collecting mirrors can be significantly reduced by sand and dust soiling, particularly in arid environments. Larger airborne sand and dust particles can also cause damage by erosion, again reducing reflectance. This work describes investigations of the airborne particle size, shape, and composition in three arid locations that are considered suitable for CSP plants, namely in Iran, Libya, and Algeria. Sand and dust has been collected at heights between 0.5 to 2.0m by a variety of techniques, but are shown not to be representative of the particle size found either in ground dust and sand, or on the solar collecting mirror facets themselves. The possible reasons for this are proposed, most notably that larger particles may rebound from the mirror surface. The implications for mirror cleaning and collector facet erosion are discussed.

INTRODUCTION

The reflectance of mirrors in the solar field of a CSP plant can be significantly reduced by sand and dust soiling, particularly in desert environments. Recovery of the reflectance requires cleaning using large soft brushes and demineralized water, a scarce and expensive resource in desert locations [1]. In addition, larger airborne particles can cause erosion of the reflecting surface, a non-recoverable effect. The effects of periodic abrasive cleaning and of sand and dust erosion can be simulated and accelerated in the laboratory, but are highly dependent on the particles used in the experiments. Previous attempts to simulate collector erosion in the laboratory have used ground sand [2]. This may overestimate the damage in real solar fields, since the larger particles will only become airborne in extreme sandstorms when the solar collectors may be protected in the stow position. When simulating the contact cleaning process, a similar overestimate may occur if ground sand is used. Most CSP plants employ a rudimentary dust barrier around the solar field, often doubling as a wind break. The impact of such a dust barrier on the mirror cleaning frequency depends on a good understanding of how airborne particles of different sizes and compositions settle on the glass collector facet surface. Therefore, an analysis of the differences between particles found at ground level, and at heights representative of parabolic trough collectors (in the range 0.5-2.0m, where we would expect the highest concentrations of soiling to occur), together with particles found on glass mirror surfaces, will be an aid to providing more accurate laboratory simulations of real solar collectors. Basically, we want to make sure that we are using the correct particle size for laboratory simulations of erosion and soiling of mirrors in various locations where CSP plants exist or could be built.

METHODOLOGY

Sand and dust particles have been collected at ground level and at four heights above ground level (0.5m, 1.0m, 1.5m, 2.0m) in three locations deemed suitable for CSP plants in Iran, Libya, and Algeria. Dust particles have also been examined on solar collector test lines at the CIEMAT Plataforma Solar de Almeria (PSA) in Spain. The apparatus for airborne particle collection was designed at Cranfield University, but built and deployed by our collaborative partners in Iran, Libya, and Algeria. The collectors consist of two separate analyzers. A simple collecting pole with adhesive surfaces collects particles at the required heights over an extended time period of typically one month, depending on the location and weather conditions. A more sophisticated analyzer exposes glass samples to natural soiling and erosion whilst simultaneously collecting dust and sand particles that fall from the glass in a shallow gutter underneath. The locations of the test stations are as follows:

(a) Shiraz Solar Power Plan is located at Dehak, near Shiraz, in the Fars Province of southern Iran. Location coordinates are: Latitude 29.3743, Longitude 52.615. The plant is a parabolic trough CSP Plant with a design capacity of 0.25 MWe.

(b) Ghadames in western Libya, weather station accessed through CSERS and University of Tripoli. Exact location given by Latitude 30°10'4.8", Longitude 9°45'21.6"

(c) Centre de Developpement des Energies Renouvelables (CDER) site in Algeria, 1.5km from Ghardaia airport with exact location of Latitude 32.38°, Longitude 3.78°.

Figures 1-3 show some details of the dust/sand particle collection poles, and the glass erosion test holders with underlying gutters to catch particles that fall from the glass.

FIGURE 1 (left): Particle collection pole (CDER, Algeria), with glass erosion rig in the background

FIGURE 2 (centre): Particle collection pole (CSERS, Libya)

FIGURE 3 (right): Detail of glass erosion holder showing particle collection gutter (common to all three sites)

RESULTS

Particle size

As an example of the results obtained in Iran, selected results from are shown in Figure 4 below.

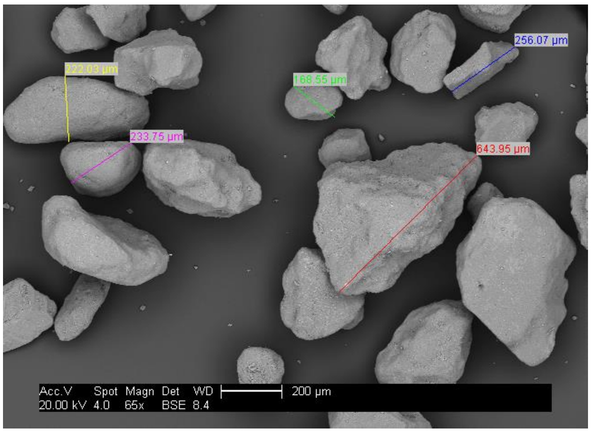

FIGURE 4a. Particles collected at ground level (Iran)

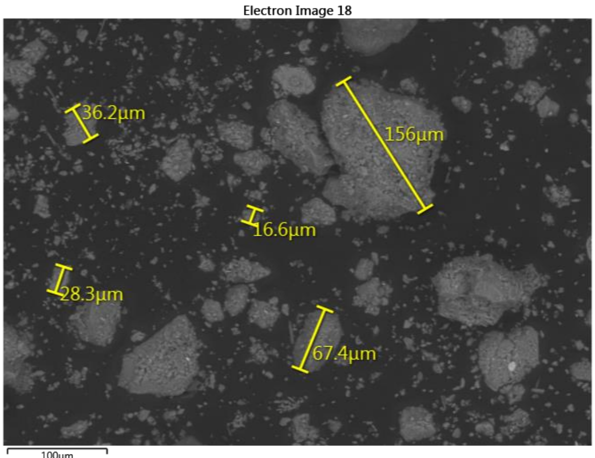

FIGURE 4b. Particles collected at a height of 1m (Iran)

These results (together with other measurements of ground sand and those of particles extracted from other heights on the pole in the range 0.5-2.0m in Iran) are broadly in line with expectations. They suggest that although larger (>500µm) particles are to be found at ground level, these particles rarely become airborne and are not found at heights above 0.5m. In Fig 4b, for example, no particles >200µm were found.

Again, that tends to support the view that particles of ≤ 200µm should be used in laboratory simulations of sand erosion of glass mirrors. The complete set of results from the Iranian sand samples are as follows. The largest particle found adhered to the pole was 335µm at a height of 1.5m (with particles up to 250µm at a height of 0.5m, particles up to 283µm at a height of 1m and particles up to 309µm at a height of 2m). The corresponding loose ground sand contained bigger particles than anything found on the adhesive pole i.e. up to 650µm. The Iranian sand is irregular in shape with rounded edges that is typical of dune rolled sand, with many smaller and flaky particles stuck to it.

Since the results from the Iranian test station were in line with expectations, the results from the weather station in Ghadames (Libya) provided something of a surprise. For the Libyan sand the largest sized particle found on the adhesive pole had a dimension of 1039µm and this was at a height of 0.5m above the ground (for completeness, corresponding largest particles for the other heights were 255µm at a height of 1m, 631µm at a height of 1.5m and 782µm at a height of 2m). The sand appears irregular and more angular in shape, but it is the particle size that is unusual. This is the only occurrence we have observed of a particle greater than 1.0 mm in our particle collection trials.

Figure 5 provides a clue as to why such airborne particle sizes are rare, but not totally unexpected.

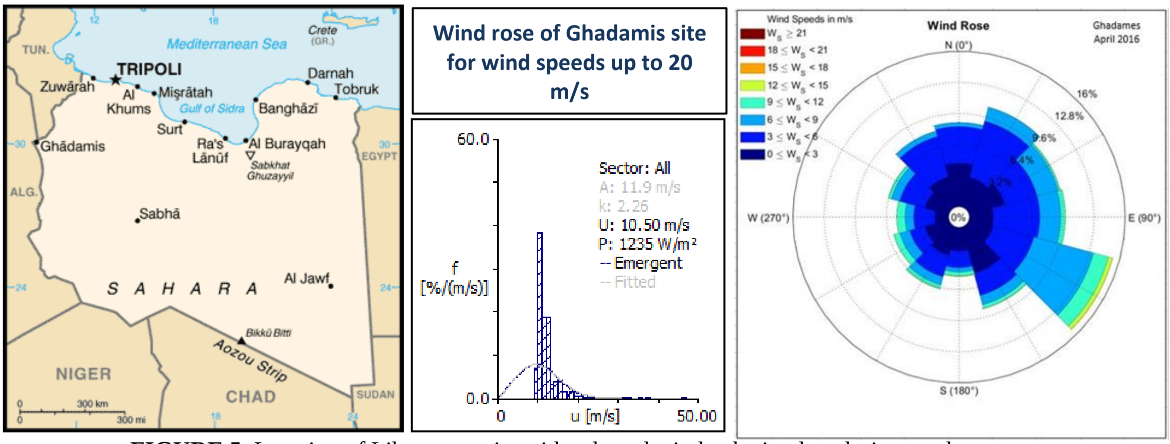

FIGURE 5. Location of Libyan test site with selected wind velocity data during sandstorms

In Figure 5 (center image) we can see the wind speed data over an 8 year period at Ghadames, in the extreme west of the country. The data shows that 7.7% of wind speed measurements exceed 9 m/sec, with wind speeds in excess of 20m/sec during those storms. Those strong winds come from the east or south-east, across the Sahara as shown in Figure 5 (left and right images), bringing airborne particles of Saharan sand and dust to eastern Libya, and Ghadames. According to Bagnold's experiments using quartz spheres [3], particles of up to 2mm can become airborne in 20m/sec winds, if they attain the wind velocity. So it seems likely that there are large (>1mm) airborne particles during high winds at all our test locations, but we have not tested long enough or taken large enough samples to capture enough of these events.

The final evidence for airborne particle size distributions in solar fields comes from inspection of full-size parabolic collector facets on test lines at the PSA in the Tabernas desert, near Almeria in southern Spain. Here, initial results suggest that only small particles of the order of 250µm or less are found to have settled on the mirror facets. These are the particles that form the natural soiling on the reflecting surfaces and are required to be removed by cleaning with brushes and water in order to regain the designed reflectance.

The difference in particles sizes observed on the adhesive poles in Libya and Iran, and the particles that have been observed on mirror facets at the PSA would appear to be contradictory. However, there is an explanation that can be tested during future work.

At the high wind speeds seen during storms (>15 m/sec, and including desert sandstorms), particles of greater than 1mm in size can become airborne. We have detected an occurrence of this in Ghadames, where sandstorms are frequent. In Iran, our experiments have not detected such large particles on the adhesive pole. The reasons for this are either that our sample size is too small and/or the wind speeds were too low (we did not have accurate wind speeds for the duration of the initial tests in Iran, but will have in future tests). The absence of larger particles on soiled collectors requires a different explanation. It is possible that the larger particles do indeed reach the mirror surface, but do not adhere to the surface, either rebounding or falling under gravity. This has implications for both erosion and cleaning of mirror facets, and is discussed later.

Compositional analysis

An example of the compositional analysis of airborne particles from Iran at a height of 1m is shown in Table 1. Here, three material types are apparent. Firstly, there are particles of silica (sand). Secondly, we see evidence of Ca, S, Na, K, Al and Fe. This points to the presence of the common minerals of gypsum, basanite, feldspars, and mica (Spectra 6-10) [2]. Thirdly, and unusually, we also found white particles containing strontium and barium, most likely in the form of sulfates or carbonates (Spectra 11-16). The Iranian particles are from a semi-urban environment, containing less sand (silica) than the Libyan Saharan samples. The source of the carbon in the Iranian sand is open to speculation. It may be evidence of organics, but a common origin in urban samples is from car tyre rubber.

Spectrum Label	C	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Zn	Sr	Ag	Ba	Total
1.0m height																			
Spectrum 6	43.68	28.86	0.79	0.96	2.49	6.62		0.83	0.35	0.87	12.46			2.08					100
Spectrum 7	34.97	36.85	0.52	1.4	3.48	11.49		0.5	0.21	1.33	5.96	0.24	0.06	3					100
Spectrum 8	31.93	39.14	0.65	1.52	4.5	12.66		0.58		3.22	1.47	0.32		4.02					100
Spectrum 9	33.01	38.34	1.77	0.83	2.76	7.14		5.3		0.89	8.05			1.9					100
Spectrum 10	40.34	31.95	0.34	0.43	1.1	2.76		7.4		0.48	14.04			1.15					100
Spectrum 11	43.77	28.35	0.13	0.41	0.9	2.69		5.51		0.38	1.01			0.7		13.75		2.4	100
Spectrum 12	63.56	16.83		0.29	0.58	1.96		3.35		0.16	1.08			0.56	0.07	10.72		0.83	100
Spectrum 13	59.65	19.76	0.18	0.15	0.59	1.32		4.31		0.13	0.9					11.69		1.31	100
Spectrum 15	57.42	21.42		0.35	0.67	1.65		4.46		0.26	1.18			0.52		11.18		0.89	100
Spectrum 16	53.59	26.26	0.52	0.39	1.18	3.08		3.61	0.14	0.39	1.27	0.07		0.77		8.73			100

TABLE 1. Compositional analysis (wt. %) of particles collected at a height of 1m (Iran)

The compositional analysis of Libyan sand provides us with additional information, since two sands were analysed from different locations in Ghadames. Sand 1 is finer, with particle sizes in the range 21 – 264μm. Sand 2 is courser, with particles sizes up to 537μm. As we have seen, all such particles can become airborne during high winds and sandstorms. The fact that fine sand is collected on one day and coarse particles on another day is a function of the wind speed. The data is shown in Table 2 below.

Spectrum label	C	O	Na	Mg	Al	Si	Cl	K	Ca	Ti	Fe	Total
SAND 1 (at. %)												
Spectrum 1		45.57	0.38	0.87	5.76	43.02		0.82	0.77	0.21	2.6	100
Spectrum 2		41.14		0.21	1.04	56.54		0.2	0.15	0.06	0.66	100
Spectrum 3		41.09		0.41	1.95	54.97		0.38	0.41		0.79	100
Spectrum 4		49.64		0.41	3.6	44.19	0.24	0.49	0.22		1.21	100
Spectrum 5		38.03		0.62	7.75	29.3		12.23		0.97	11.1	100
Spectrum 6		51.59		0.66	3.79	41.34	0.23	0.57	0.44	0.12	1.26	100
Spectrum label	C	O	Na	Mg	Al	Si	Cl	K	Ca	Ti	Fe	Total
SAND 2 (at. %)												
Spectrum 7		44.09	0.13	0.98	1.42	52.08			0.3	0.27	0.73	100
Spectrum 8		38.83	0.24	5.09	3	49.65	0.99	0.65			1.55	100
Spectrum 9		46.85	0.59	2.71	10.49	27.3	0.71	8.29	0.91	0.26	1.88	100
Spectrum 10		50.6	0.21	1.07	2.23	44.48	0.39	0.37			0.66	100
Spectrum 11	5.85	49.58		14.25	1.51	6.26	0.57		21.51		0.48	100
Spectrum 12		55.8		2.29	1.04	39.69	0.38	0.17	0.28		0.35	100

TABLE 2. Compositional analysis of two ground sand samples from Ghadames in Libya

The two samples shown in Table 2 are similar in many respects, but the sample containing the larger particles does include sodium and chlorine traces which are not present in the smaller particles. This suggests the presence of halite or rock salt in SAND 2. In Table 1 and Table 2 note that each spectrum is an EDAX (Energy Dispersive Analysis by X-ray in the scanning electron microscope) measurement from a single particle. The tabulated results are from a small random sample of particles, and are intended to give an indication of the elements present in the sample and their relative proportions.

Reflector erosion and implications for simulating cleaning and erosion of mirrors

Preliminary results indicate that sand and dust particles of up to 1mm become airborne in sandstorms and strong winds in locations representative of those suitable for CSP plants, with the particles likely to achieve velocities of up to 20m/sec. However, for reasons that we do not fully understand, we have found no evidence for particles greater than 250μm having settled on a parabolic mirror facet, even after considerable soiling has occurred. This has implications for simulating the contact cleaning and sand erosion processes in the laboratory, where we attempt to use sand/dust particles that are appropriate for the location. This is particularly true of particle size, since erosion is critically dependent on the particle size.

Often, laboratory simulations of sand erosion processes utilize particles of 250μm or less. This may lead to an underestimation of the erosion damage. Particles of 1mm (which we have detected at heights that correspond to the lower facets of a standard parabolic trough) have more than 50 times the energy of a particle of size 250μm. The rarity of these particles in our samples suggests these are not likely to be frequent collisions, but they will be damaging to glass at wind speeds above 15 m/sec.

For contact cleaning processes, we have a different conclusion. Here, for reasons that are not entirely clear, larger particles do not appear to adhere to the glass surfaces. This has implications for contact cleaning simulations in the laboratory, where particles of sizes greater than 250μm have sometimes been used in experiments (including the current authors). There are also implications for the design and testing of dust barriers around solar fields. If larger particles are not found to settle on glass mirrors, they are not the deciding factor in determining the efficiency of a CSP plant dust barrier.

CONCLUSIONS

This paper describes work in Iran, Libya, and Algeria to design, construct, and deploy equipment to determine the size and composition of airborne particles up to a height of 2m in arid regions where CSP plants are likely to be located. The results are compared with samples taken at ground level. The results indicate that although soiling on mirrors in real parabolic trough solar fields appears to only consist of particles up to 250μm in size, larger particles (up to 1mm) can become airborne in sandstorms and other strong winds (above 15 m/sec). The collisions of these larger mm-scale particles with the glass mirror facets may be very infrequent events, as shown by our sand and dust particle collection results, but they will be damaging to the mirrors if the impact occurs at velocities approaching the wind speed. This work can also inform laboratory simulations of cleaning and sand erosion. For mirror cleaning experiments, the larger particles (>250μm) do not need to be considered. For reasons that are not entirely clear, these particles do not appear to remain on the mirror surface after impact. For laboratory simulations of sand and dust erosion of mirror samples [4] the protocol now has additional complexity. It may be necessary to consider infrequent collisions of high-speed larger (up to 1mm) particles within a much larger number of smaller (up to 300μm) particles. Finally, when considering dust barriers in order to reduce the frequency of mirror cleaning, our initial results suggest that it is only particles of sizes up to around 250μm that actually soil the mirrors and reduce the reflectance.

It should be noted that these are initial results, and more work is scheduled in order to confirm these findings and investigate the causes of the particle behavior reported in this paper. Although particle detection systems have been deployed in Algeria, no results have yet been analyzed. The correlation of elemental composition with particle size is one area for further analysis. Further analysis of the particle distributions in samples is also required, together with detailed measurement of particles found on solar collectors at the PSA. Finally, particles captured in the gutter systems have yet to be assessed.

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