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DUST CHARACTERISATION FOR SOLAR COLLECTOR DEPOSITION AND CLEANING IN A CONCENTRATING SOLAR THERMAL POWER PLANT

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ABSTRACT

Solar collectors (mirrors) suffer from the dust deposition which requires frequent cleaning to maintain their efficiency. Since hundred thousand square meters of solar mirror are required even for a relatively small solar power plant, the cleaning on such a large mirror surfaces involves a significant operation and maintenance (O&M) activities and cost in concentrating solar thermal power plants.

Dust deposition on solar mirror surface is site specific and the dust characterisation for each site is required in order to optimize the solar mirror cleaning activities. Based on this factor, a dust monitor has been installed in a proposed solar thermal power plant in Australia to collect the data of dust and the weather conditions. A metallic test bench with different solar mirrors has also been installed in the same site to correlate the surface deposition and the reflectance of the solar collectors. The results showed that the average dust size were less than 20µg and over 90% of the dust concentration were lower than 30µg/m^3 during the one year monitoring period. The reflectivity of solar mirrors decreased from the original 92% to about 20% after a month, during which zero rainfall was recorded.

INTRODUCTION

The effect of dust particles on solar mirror surfaces is to deflect or scatter incident light rays. For concentrating solar thermal (CST) power plants, even a small deflection will cause the rays to miss the target (receiver) and not be collected (Bergeron and Freese, 1981). As a result, CST power plants will lose production. Therefore, regular mirror cleaning is essential and it forms an important part of the operation and maintenance (O&M) activities in solar thermal power plants to maintain high reflectivity of the mirrors.

Effect of dust on the performance of various CST systems has been carried out by many researchers (Elminir, et al, 2006, El-Nashar, 2009 and Moharram, et al, 2013). Niknia, et al (2012) reported that an amount of 1.5 g/m^2 dust could reduce the instantaneous performance of parabolic trough collectors (PTCs) up to 60% and the average performance during the dust deposition up to 37%. Experience from Spain showed that, in summer, the PTC reflectivity rapidly decreased at a rate of about 0.0025% per day during the first two weeks after washing the PTC system (Lovegrove and Stein, 2012). Strachan et al (1993) studied the effect of dust on the degradation of heliostat efficiencies. On the average, soiling reduced mirror reflectivity of the heliostats by 6.3 and 8.8% respectively for the two types of heliostats in their study. Blackmon (1978) observed that the reflectance losses were about 7.2% and 11% for the glass and acrylic mirrors of the heliostat respectively after a storm.

Dust is the dominant source for solar collectors deposition in CST power plants and regular cleaning is required to recover the reflectance lost caused by mirror deposition. The effective cleaning method has to address the significant characteristics of dust such as the size, distribution, density, shape, composition, chemistry and charge. Shao (2008) showed that the particle sizes range from 20 to 70 µm has short-term suspension and the long-term suspension particles must be less than 20 um. This indicates that the particle size deposit on solar mirror should be less than 70 µm if the airborne dust is the main cause for mirror deposition according to this study.

The significant characteristics of dust are site specific. The influence of dust on the reflectance of solar mirrors is a complex function of dust deposition behavior, the accumulation rates and the exposure conditions. Effective mirror cleaning strategy is strongly dependent on dust composition, particulate size of the dust, relative humidity, rainfall, wind, temperature, and the materials of the mirrors used. Therefore, effective cleaning (method and frequency) is site specific: it depends on the dust load and the dust property at the specific site.

A dust monitor, E-sampler, has been installed in a proposed Australian CST site to collect real time dust concentration, wind speed, wind direction, humidity and temperature. Dust samples (for size analysis) were collected on filters which can be inserted in the dust monitor. A metallic test bench has also been installed in the same site to correlate the surface deposition and the reflectance for difference mirror materials. In this metallic test bench, 10 mirror samples with size of 400×400 mm (0.5mm thickness) are arranged in 2 rows and 5 columns. The first row of the mirrors is left for dust accumulation for certain time period without cleaning and is used as the test samples for the study on effective cleaning. The second row of mirrors is cleaned regularly and their reflectivity is measured before and after each cleaning. The dust deposited on each mirror was also collected after each cleaning for the property analysis in lab.

With the real time dust data collected from the dust monitor as well as the dust samples collected from both the dust monitor and the solar mirrors, an analysis of dust rates and dust property were undertaken to determine the level of soiling at a proposed Australian CST site. The results should lead to the development of a cost effective cleaning system for the proposed CST site and other CST sites in general.

DUST MONITORING AND DUST SAMPLE COLLECTING DEVICES

An Ecotech E-Sampler was selected for providing real time dust monitoring and dust sample collection. The E-sampler incorporates dual technology that combines light scattering technology and gravimetric method, each with strengths and weakness (Met One Instruments, 2011). The light scattering technology uses light scatter from suspended particulate to provide a continuous real-time measurement of airborne particulate. Gravimetric method uses a 47 mm filter system for filtration of dust and the dust sample collection.

The dust monitoring system includes the E-Sampler, a solar power panel, a wind speed and direction sensor, a humidity sensor and a mounting frame as shown in Figure 1.

Fig. 1 The E-Sampler used for collecting the real time dust, weather conditions and dust samples

One of the uses for the 47 mm filter element is a gravimetric calibration of the continuous light scatter measurement since all light scatter devices have inherent difficulties when converting light scatter to mass. The simplest solution is to compare the light scatter concentration for a set period of time with a gravimetric concentration over the same period of time. Comparing the concentrations will yield a K-factor that can be entered into the E-Sampler. The other use of the 47 mm filter is to collect the dust sample for the dust size and properties analysis. The 47 mm filter can be easily inserted as shown in Figure 2.

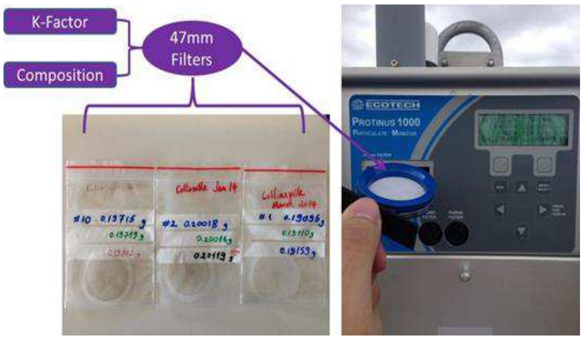


Fig. 2 Dust sample collection with 47mm filter for properties analysis

The real time data are downloaded remotely through a 3G modem. All data can be downloaded in offices located anywhere.

The deposition of dust on different mirror materials was collected by using a metallic test bench and the reflectivity of each mirror was measured by the reflectance meter, 410-Solar. Figure 3 illustrates that five different materials of mirrors are placed on the bench. 10 samples with size of 400×400 mm (0.5mm thickness) are arranged in 2 rows and 5 columns. The first row of the mirrors are to be left for dust accumulation for certain time period and they will be used as the test samples for spray cleaning in QGECE's wind tunnel. The second row of surfaces was cleaned regularly and their reflectivity was measured before and after each cleaning. By doing this, the mirror surface degradation due to the dust deposition and the effectiveness of mirror cleaning can be identified.

When washing each mirror, dust was also collected by collecting both the water and dust. After the water is filtered out, the dust is characterized to determine the interaction between dust and mirror materials.

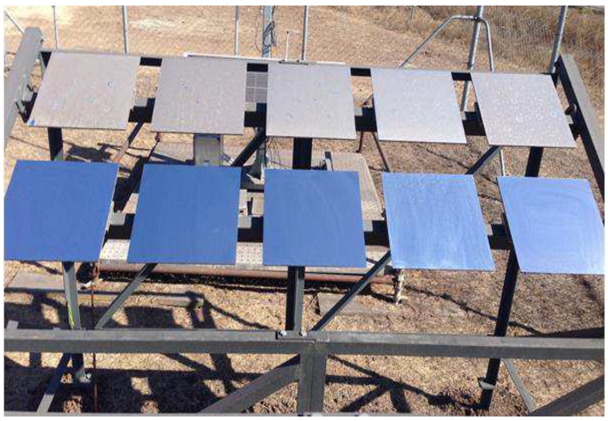


Fig. 3 The test bench installed for dust sample collection and degradation study on different mirrors

DUST CHARACTERISATIONS

Dust concentration, dust size and property, ambient weather conditions were recorded by the dust monitor for a year and are presented in this section. The average temperature and particle size in the following sections were calculated with the arithmetic mean unless otherwise specified.

Statistical analysis on dust concentration and weather conditions

The histogram of dust concentration during one-year monitoring period with the E-sampler is plotted in Figure 4. The dust concentration of more than 100μg/m^3 had very low frequency. The highest occurrence of dust concentration was about 10μg/m^3 and over 90% of the dust concentration were lower than 30μg/m^3 during the 12 month monitoring period.

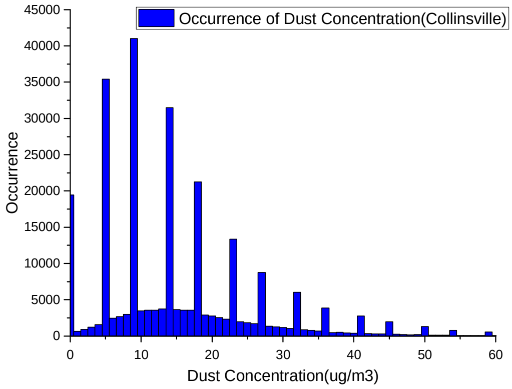


Fig. 4 Histogram of dust concentration in 12 month monitoring period

Figure 5 plots the statistic data collected in April (23/4/14 – 30/4/14) which has the average dust concentration close to the average value in one-year period. It can be clearly seen that over 90% of the dust concentration are lower than 30μg/m^3 in this week.

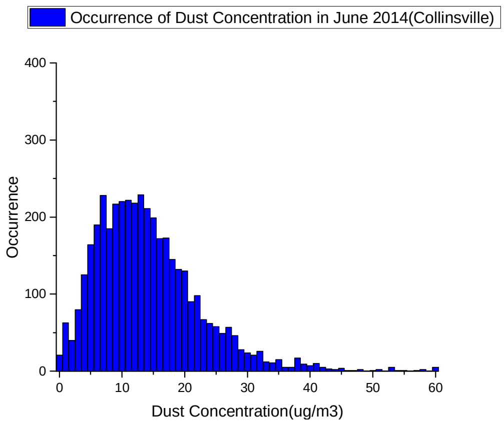


Fig. 5 Histogram of dust concentration in April 2014

The histogram of wind speed collected in the same one-year period is plotted in Figure 6. Over 90% of the wind speeds were lower than 5 m/s. The average wind speed was about 2m/s.

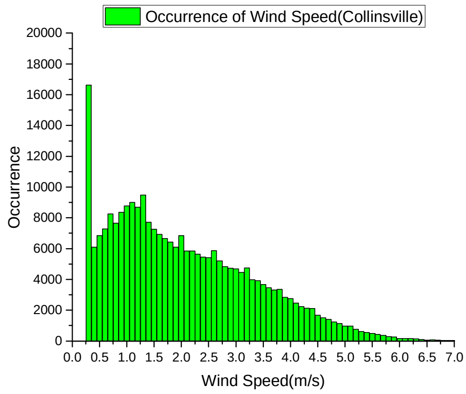


Fig. 6 Histogram of Wind Speed in the 12 month monitoring period.

Figure 7 shows the frequency of wind direction. The majority of the winds were the South-East wind.

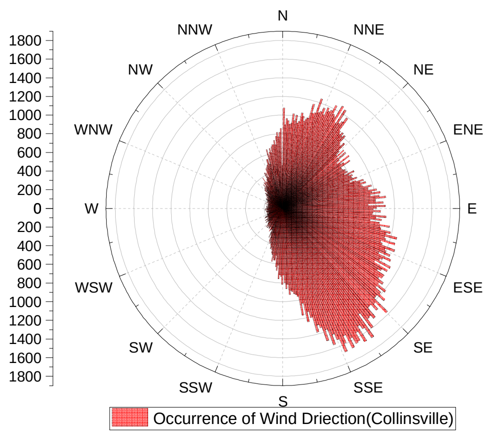


Fig. 7 Histogram of Wind Direction in the 12 month monitoring period.

The average temperature in each month in this site is shown in Figure 8. Based on the raw temperature data collected, the highest temperature was 44.3°C in summer noon (January in Australia), and the lowest temperature was 3.7°C in the winter night (July). The average temperature was about 27°C in summer and 15°C in winter.

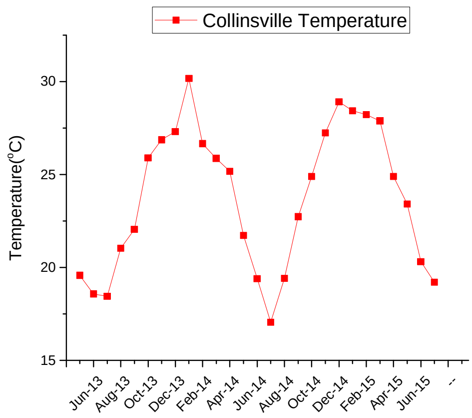
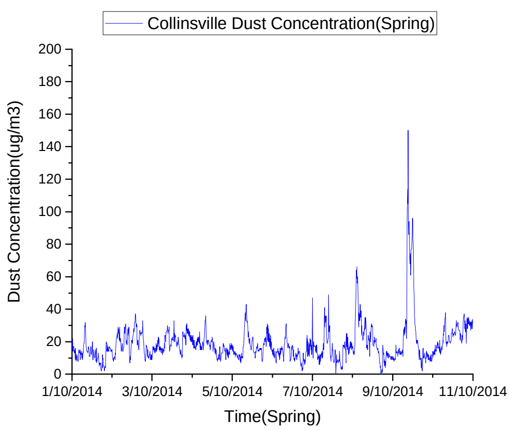


Fig. 8 Monthly average temperature variation in the proposed solar plant site

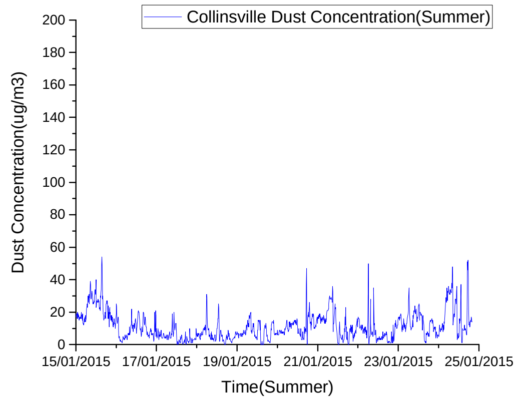
Time history of dust concentration

Although the E-Sampler measures the particulate concentration and updates the display each second, the fastest average period that can be logged in memory is one minute. In our monitoring period, five minute output average was used. However, 15 minutes average time was used when the filters was inserted for calibration, which leaves enough time for dust accumulating on the filter while one does not need to worry the data downloading due to the memory limitation of the system.

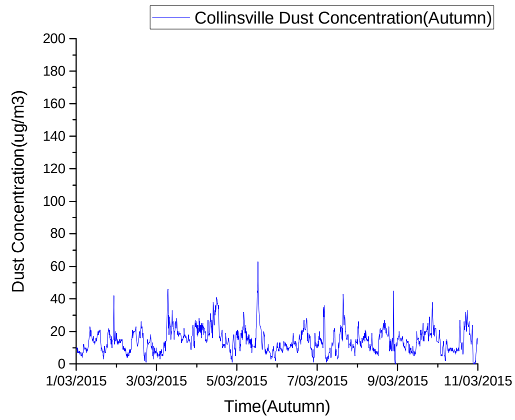
Dust concentrations collected in different seasons, which were spring (01/09/13-18/09/13), summer (01/01/14-09/01/14), autumn (01/04/14-10/04/14) and winter (05/08/13-14/08/13), are plotted in a, b, c and d in Figure 9, respectively. Although the maximum dust concentration of 1472µg/m^3 was detected in a very short period in winter (Fig. 9), the average dust concentration was about 13µg/m^3 in this winter period. There were some high dust concentrations occurred in spring (Fig. 9a) but the average dust concentration was about 18µg/m^3, which is the highest in average in those four periods. The average dust concentration in autumn was 14µg/m^3 and 11µg/m^3 in summer.



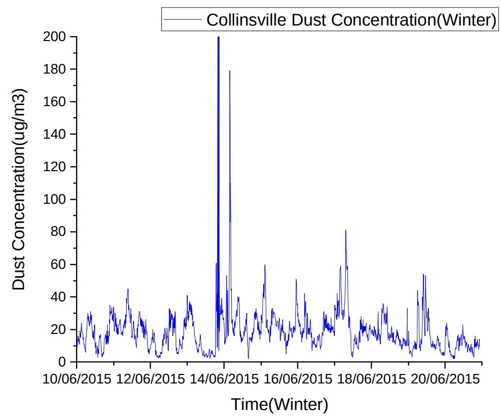
a) Spring



b) Summer



c) Autumn



d) Winter

Fig. 9 Time history of dust concentration recorded different seasons.

Figure 10 presents time history of dust concentration in one day and it seems that higher dust concentration happed from 4:00am to 12:00 pm during that period. More than 20µg/m^3 was observed quite often on the 5th of May in the morning.

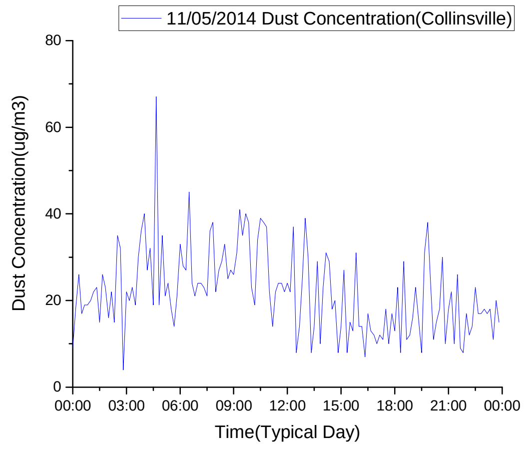


Fig. 10 Time history of dust concentration for a typical day.

Dust size and properties

The dust samples collected from the site on the three filters inserted in the dust monitor were analyzed in the Queensland University of Technology (QUT) lab with the equipment of scanning electron microscope (SEM). All typical dust particulates were analyzed based on their characteristic shapes: such as rod, cube and uneven. Figure 11 shows an electron image of the dust deposited on the filter during January 2014. The average particle size was about 15 µm but more than half of the dust sizes were over 20 µm.

The dust size and properties collected on these three filters are summarized in Table 1.

The Collinsville mine was closed during those three sampling months, and it means the differences of dust composition were caused by airborne soiling travelled with different directions of winds. Mirror dust samples were obtained in March 2015 during Collinsville Mine operation.

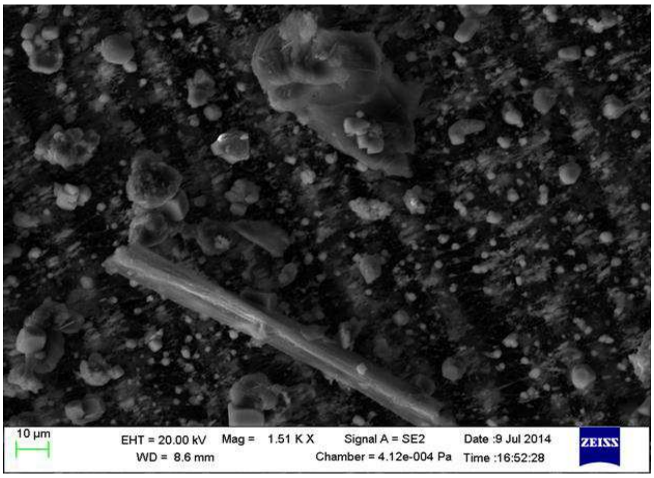


Fig. 11 Electron image of the dust collected in Jan. 2014 on the 47mm filter.

Table 1 Dust size and properties collected on the three 47mm filters

Collected periods	Particle size	Shape	Properties
Jan 2014	Average 15 µm Half>20 µm	Cubic (90%) Rod Uneven	Sodium & Chlorine Sodium, chlorine, & magnesium Silicon & aluminum
March 2014	Average 18 µm A few more than 100 µm	Cubic (75%) Rod Uneven	Sodium & Chlorine Sodium, Chlorine, & magnesium Silicon
April 2014	Average 15 µm Half>20 µm	Large size (>20um) Fine size	Silicon & aluminum Silicon

MIRROR SURFACE DEPOSITION

The real time data collected from the E-sampler and the dust samples from the 47mm filters were the air suspension dust with average dust size less than 20µm as shown in Table 1. According to Shao's study (2008), the particle sizes range from 20 to 70 µm has short-term suspension and the long-term suspension particles must be less than 20 µm. This indicated that particle sizes larger than 20 µm have more chance to deposit on the solar mirror. To determine how these dusts deposit on solar mirror surface and what the effect on the mirror performance is, a metallic test bench was installed.

As shown in Figure 3, the first row of the mirrors were left for dust accumulation for certain period and they were used as the test samples for the effective spray cleaning research. The second row of surfaces was cleaned regularly and the dust was collected after each cleaning. The reflectivity of each solar mirror was measured before and after each cleaning.

Figure 12 plots the reflectivity of all mirrors placed on the first row in the test bench without cleaning. It can be seen that the reflectivity dropped from the original 93% to about 20% for the 3M mirror after about one month exposed to the environment. The reflectivity increased to about 80% a month late and kept at about this level for the rest of time for six months.

The first big drop in the reflectivity was caused by a thick layer of dust accumulation on the mirror surfaces as clearly seen in Figure 13. Natural wash (rain) causes the reflectivity increase from 20% to about 80% from 11 September 2014 to 1 October 2014, a relatively clean mirror surface can be observed from the photo.

Among the seven mirrors (two mirrors were added late) installed on the first row of the bench, six mirrors showed the similar trend of the reflectivity change. Only one mirror behaves differently which indicated that the mirror cannot be cleaned to recover its reflectivity at the same level as the other mirrors.

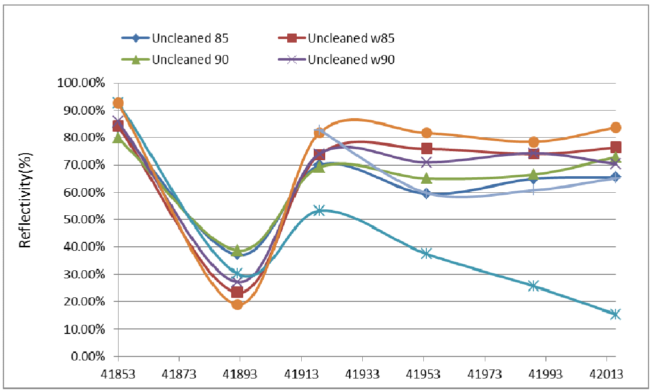


Fig. 12 The reflectivity measured for the mirrors without cleaning during 6 months.

Figure 13 shows the photos taken for 3M mirror at different time to demonstrate the dust accumulated on the mirror surface. The mirror was new when the photo was taken on 2nd August 2014. The mirror was the dirtiest one on 10th September 2014 since no rain was recorded during that month. Several rain events were recorded in a weather station after 10th September 2014 as indicated in Figure 14.

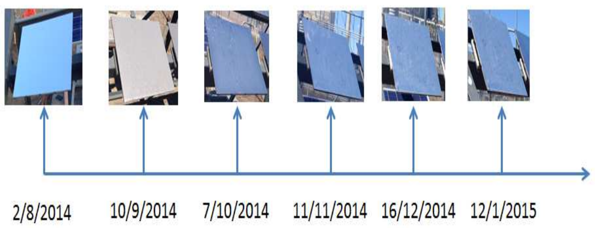


Fig. 13 3M mirror on the first row of the bench without cleaning – photos taken before each cleaning on the second row of mirrors during 6 months.

Figure 14 compares the reflectivity of the 3M mirror at the state of unclean (on first row), before and after clean (on second row). The rainfall recorded is also presented in this figure and the value was shown on the vertical axis at right hand side. On 2 August 2014, the mirror was installed on the test bench with the reflectivity of 93%. On 10 September 2014, the reflectivity dropped to about 20% for both mirrors placed on the first and second rows and no rainfall was recorded during the month. The reflectivity of the 3M mirror on the second row was recovered to about 89% after the manual washing. On 7 October 2014, the reflectivity of the mirror on the first row was slightly higher than the reflectivity of the mirror on the second row even after it was cleaned. This may be caused by either the measuring error or the ineffective manual cleaning method. The ineffective manual cleaning was also observed from the insignificant difference of the reflectivity measured before and after cleaning on the mirror. Since then, a squeegee cleaning was introduced late on 11 November 2014.

After the introduce of the squeegee cleaning on all mirror surfaces, the results showed consistent trend: the reflectivity of the mirror after cleaning is always higher than that before cleaning; and the reflectivity of the mirror (second row) before cleaning is always higher than that of the mirror on first row (without cleaning). A heavy rainfall of about 100mm was occurred three days before 16 December 2014 but did not improve the reflectivity of the unclean 3M mirror on the first row much. In general, about 10% improvement in reflectivity can be achieved after each cleaning while comparing with the unclean mirror on first row and about 5% improvement has been achieved while comparing the same mirror after the cleaning. The improvements are based on the reflectance measurement by a reflectance meter, 410-Solar. The reflectance measurement was carried out each time before and after the mirror wash. By doing this, the mirror surface degradation due to the dust deposition and the effectiveness of mirror washing was identified.

The correlation of the average dust concentration recorded by the dust monitor and the reflectivity of the 3M mirror is shown in Figure 15. It seems that there is no direct correlation between the average dust concentration in the air and the reflectivity of the solar mirror during the monitoring period. This could be due to either the air was relatively clean or the average concentration may not be a good indicator for this correlation. Instant or short time high dust concentration may play a more important role for dust deposition on the mirror surface.

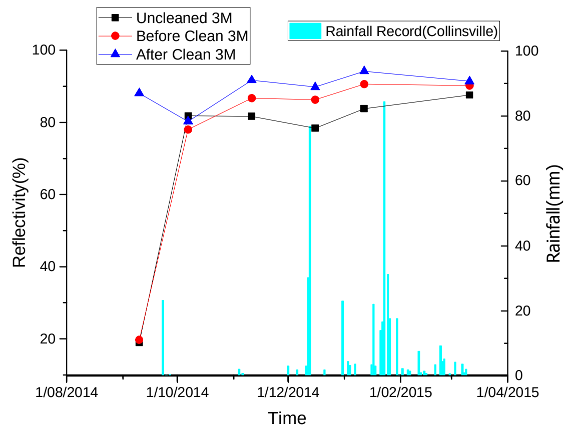


Fig. 14 Comparison of the reflectivity for 3M mirror at different states of cleaning.

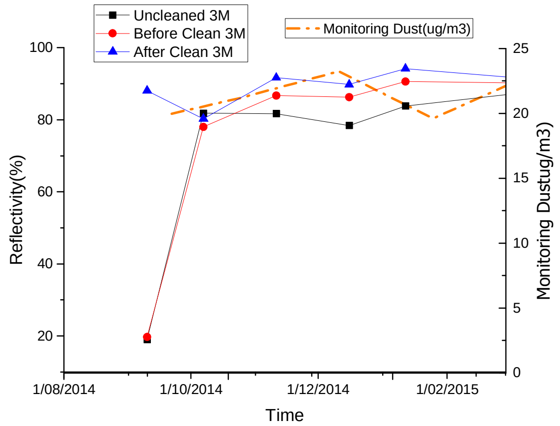


Fig. 15 Correlation of the dust (recorded by the dust monitor) and the reflectivity of the 3M mirror.

DISCUSSIONS AND CONCLUSIONS

Selecting a cost effective cleaning method and the cleaning frequency for CST plants is site-specific since the density of the dust deposited on solar mirror depends on the rate and natural of dust accumulation, particulate size of the dust, the materials of the mirrors used, and the ambient conditions like relative humidity, rainfall, wind, and temperature. Therefore, collecting these data becomes an important first step.

Solar mirror made of different materials may respond differently to each cleaning method and may require different cleaning frequency.

On the basis of the discussions described above, the following conclusions are presented:

1. Real time dust concentration collected in the proposed site has been quantified. The highest occurrence of dust concentration is about 10μg/m^3 and over 90% of the dust concentration are lower than 30μg/m^3. In average, the dust concentration was about 11μg/m^3 in summer, 13μg/m^3 in winter, 14μg/m^3 in autumn and 18μg/m^3 in spring.
2. Ambient weather data including wind speed, wind direction, humidity and temperature have been monitored and recorded to gain an understanding of the processes which govern the dispersion and transport of dust from nearby sources. Over 90% of the wind speeds were lower than 5 m/s. The average wind speed was about 2m/s. The average temperature was about 27°C in summer and 15°C in winter.
3. The average size of dust particles is around 15μm in the proposed site, and the composition of the dust is mainly sodium, chlorine, silicon, aluminum and magnesium.
4. The reflectivity of the solar mirror decreased from 93% to about 20% after one month exposure to the environment during zero rainfall periods.
5. Natural washing (rain) can clean the mirror quite effectively before the contaminant accumulation by cementation of water-soluble salts (caused by weather, such as dew and high humidity) and is ineffective once the contaminant accumulation occurred (such as the heavy rainfall cannot help in December).

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