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Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules

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Deposition of airborne dust on outdoor photovoltaic (PV) modules may decrease the transmittance of solar cell glazing and cause a significant degradation of solar conversion efficiency of PV modules. Previous studies of this issue indicated that dust deposition is closely related to the tilt angle of solar collector, exposure period, site climate conditions, wind movement and dust properties. However, few studies considered the influence of the properties of PV module itself on dust deposition and efficiency degradation, such as the cell types and surface materials. This experimental work aimed to study the dust accumulation onto different types of solar PV modules and the corresponding efficiency degradation. The experiment was designed and conducted in the laboratory with a sun simulator and a test chamber. The degradation of PV module efficiency caused by dust deposition under various conditions was investigated. The results indicated that dust pollution has a significant impact on PV module output. With dust deposition density increasing from 0 to 22 g m^{-2}, the corresponding reduction of PV output efficiency grew from 0 to 26%. The reduction of efficiency has a linear relationship with the dust deposition density, and the difference caused by cell types was not obvious. When the dust deposition density was fixed, the reductions of output efficiency at relatively lower or higher solar densities were much more severe. Moreover, the surface material may influence dust deposition and accumulation considerably. The polycrystalline silicon module packaged with epoxy degraded faster than other modules with glass surface under the same dust concentration.

1. Introduction

Due to its advantages in both technological and economical aspects, solar photovoltaic (PV) industry has been expending worldwide. In China, the reported demand for new solar modules is as high as 232 MWp each year from now to 2012. The government announced to expand the installed capacity to 1800 MWp by 2020. Typically, the solar conversion efficiency of PV modules ranges from 10 to 13% in commercial level. However, the efficiency of outdoor installed PV modules may be further reduced by 10–25% due to the losses in the inverter, wiring and dust pollution (Denholm et al., 2010). The losses due to dust pollution can be significant especially for the areas with high dust concentration levels, such as the northern west of China and many urban cities of China where with the highest installation of PV modules. For example, in many urban areas, the mass concentrations of ambient TSP ($d_p < 100$ μm) and PM10 ($d_p < 10$ μm) have already exceeded the annual arithmetic average of the National Ambient Air Quality Standard (NAAQS), with 200 mg m^{-3} for TSP and 100 mg m^{-3} for PM10 (State Environmental Protection Administration, 2004). The high concentrated deposition of airborne dust may decrease the transmittance of cell glazing and cause a significant degradation of solar conversion efficiency (Mani and Pillai, 2010).

The previous studies of dust deposition on solar panels focused on the outdoor investigations of glazing transparency performance. For example, Salim et al. (1988) studied the PV array energy output near Riyadh (Saudi Arabia). Due to the effect of dust accumulation, 32% reduction in energy output was observed in eight months. El-Nashar (1994) examined the effect of dust accumulation on the performance of solar collectors over different time periods in the United Arab Emirates. The monthly decline rate in glass transmissivity was between 10% in summer and 6% in winter, and a 70% reduction in the collector performance was observed for a whole year. Hegazy (2001) conducted a year-long experiment in central Egypt for the subtropical climatic region. An expression of glass transmittance reduction in one month was derived based on their experimental data. Hassan et al. (2005) found the degradation progressed rapidly during the first 30 days of exposure. Elminir

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et al. (2006) studied the effect of dust coverage on the transmittance of glass samples with different tilt angles. They showed that the dust deposition densities vary from 15.84 g m^{-2} to 4.48 g m^{-2} with a tilt angle from 0° to 90° and the corresponding transmittance diminishes by 52.54%–12.38% respectively.

Correspondingly, experimental researches in laboratories under controlled conditions were conducted since 1990s. El-Shobokshy and Hussein (1993) firstly investigated the impact of dust properties and deposition density on the PV efficiency. The results showed that fine particulate dust has a greater impact on performance of PV panels than coarser particles. Al-Hasan (1998) experimentally and mathematically studied the effect of sand dust layer on beam light transmittance at a photovoltaic module glazing surface. They found that longer wavelengths are reflected much more than shorter ones as the amount of sand dust particles increases on the glass samples. Goossens et al. (1993) and Goossens and Kerschaever (1999) carried out wind tunnel experiments on the influence of wind velocity and direction on dust deposition onto PV system. Their studies indicated that the drop in PV cell performance grows larger as wind speed increases.

In a word, it can be concluded that dust accumulation on solar transmittance is closely related to the tilt angle of solar collector, exposure period, site climate conditions, wind movement and dust properties. However, few studies paid attention to the properties of the module itself, such as the type of solar cell and the surface material of solar module. In current solar market, the vast majority types of solar cell are the mono-crystalline silicon, ploy-crystalline silicon and the amorphous cells. The mono-crystalline and poly-crystalline panels have higher output efficiency and the power outputs greatly depend on the solar radiation received by the panels. Whereas the amorphous panel is with relatively low efficiency, but it works even and better with the diffused radiation. Accordingly, the dust accumulation may influence the different solar panels in different ways. Furthermore, the degradation is directly determined by the duct accumulation on module surface. The materials of the module surface would have an effect on dust deposition. According to the studies of indoor aerosol deposition, it has pointed that the deposition velocity of airborne dust onto different types of surfaces were quite dissimilar to each other (Hamdani et al., 2008).

This paper aims to investigate the output degradation of different types of PV modules with different surface materials caused by airborne dust pollution experimentally. A series of experiments under controlled conditions were designed and conducted. The influences of dust pollution on three different solar modules were studied and compared. This work will help select module type and the cleaning method for different applications based on the understanding of dust deposition on PV surface and characteristics of efficiency degradation.

2. Experimental methodology and materials

The main objective of this project is to characterize the influence of airborne dust on the performance of solar PV modules. Most of the previous works conducted outdoor experiments to investigate the influence of dust deposition on glass transmissivity or PV panel's output. Nevertheless, experiments under controlled conditions can give more accurate and reliable data. In this project, a laboratory experiment under controlled conditions was designed and processed.

2.1. Experiment methodology

When processing the experiment in laboratory conditions, the difficulty is to simulate a natural dust deposition process. Therefore, an experiment setup with a test chamber was designed and built. The schematic flow chart of the setup is shown in Fig. 1, which mainly includes four parts: the test chamber, the sun simulator, the airborne dust generator and the measure systems. The test chamber (1 m × 0.6 m × 0.6 m) was made of ESD acrylic plate which is highly transparent and anti-static. Test duct was injected into the test chamber and mixed with the air under the movement of a small fan, then the dust slowly and naturally deposited on the PV module which was placed in the middle of the chamber. The test dust was injected by a dust generator (RBG 1000, PALAS) and its concentration and size distribution in the chamber was monitored by a Particle Counter (LASAIR II).

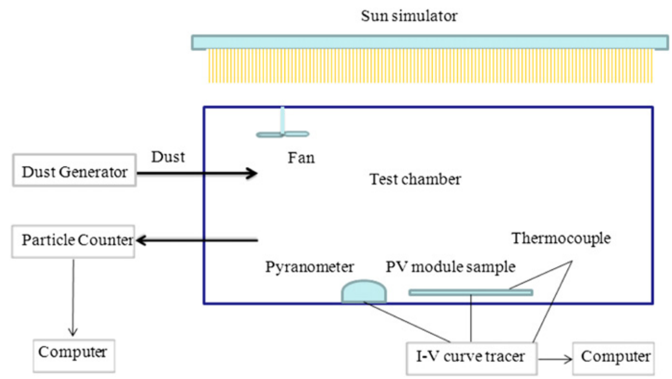

Fig. 1. An illustration of lab experiment setup.

A sun simulator (Fig. 2) was used to provide the simulated sunlight which has an output power range from 0 to 1000 W m^{-2}. Light can be directly irradiated into the chamber and the reference radiance to the PV module was given by a pyranometer (MS-402).

To make sure that the current sun simulator can provide enough irradiance into the test chamber and estimate the potential effect of test chamber on light reflection, a Xenon lamp solar simulator (Fig. 3) was also utilized here. The Xenon lamp solar simulator provides reliable sunlight simulation and is commonly used in repeatable testing of PV modules. However, the exposure area of this equipment is too small to conduct chamber test, and sun simulator with a measurement system is thus adopted as the major testing apparatus of irradiance. In this work, the performances of PV module indirectly exposed to the sun simulator and directly exposed to the Xenon lamp solar simulator were measured and compared.

The *I*–*V* curve of PV module was measured by an *I*–*V* curve tracer (MP-160) to characterize PV module's output. The temperature of the module was measured by a T-type thermocouple. The background temperature and humidity of this experiment were controlled by the air condition system. The temperature of PV module was around 25 °C and the related air humidity was about RH = 60%.

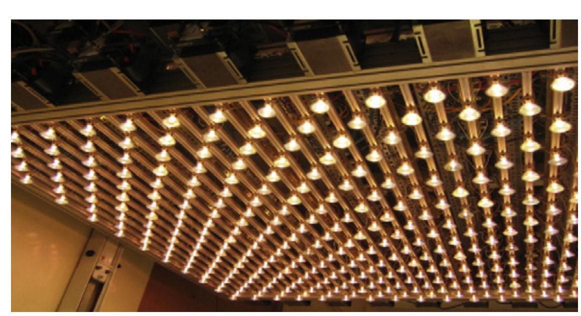

Fig. 2. Photo of the sun simulator.

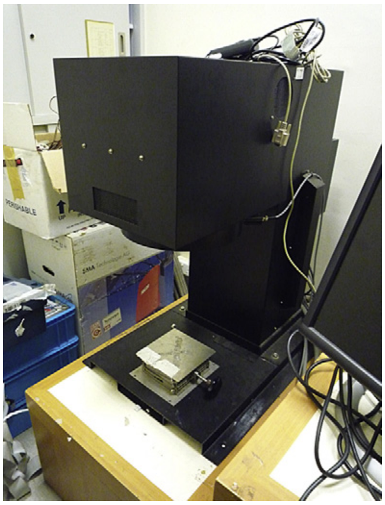

Fig. 3. Photo of the Xenon lamp solar simulator.

2.2. PV modules

Three pieces of PV modules were tested in this work, as shown in Fig. 4. The parameters of the PV modules were given in Table 1. Module 2 was packaged with epoxy and the other two modules were covered with glasses.

2.3. Test dust

To match the natural dust pollution, the fine test dust (ISO 12103-1 A2, Powder Technology Inc.) was used in this work. Fig. 5 gives the dust size distribution by volume percentage according the data of Powder Technology Inc. The test dust has a multi-distribution sized from 1 μm to 100 μm, in which the volume of dust with size of 20 μm is about 20% and the sum volume of dust less than 20 μm is about 74%. The specific weight of the dust is 2.65 g cm^{-3}. The chemical components of dust are basically SiO_2 and Al_2O_3 and the weight percentage of chemical components can be found in Table 2.

3. Results and discussion

3.1. Irradiance test

The performances of solar module 1 placed in the test chamber under sun simulator and directly exposed to the Xenon lamp solar simulator were firstly measured and compared. Fig. 6 demonstrates the comparison of the I–V curves of module 1 under different solar simulators at the irradiance level of 400 W m^{-2}. It can be seen that, the two profiles are closed to each other. Both the short circuit

Table 1
Parameters of the PV modules.

Module	Cell type	Surface material	Size (mm^2)
1	Mono-crystalline silicon	White glass	125 × 125
2	Poly-crystalline silicon	Epoxy	125 × 125
3	Amorphous silicon	White glass	125 × 180

current I_{sc} and the open circuit voltage V_{oc} are almost the same for two simulators. This result proved that the radiance in the test chamber provided by the sun simulator has no different with the one which was directly offered by a Xenon lamp solar simulator. The light reflection effect of the test chamber can be ignored.

3.2. Effect of dust deposition density

The effect of dust deposition density on the output performance of solar modules was investigated. The dust deposition density was determined by measuring the weights of PV modules before and after duct accumulation, respectively. Fig. 7 gives the variation of normalized short circuit current $I_{sc}/I_{sc\ \mathrm{clean}}$ of the three modules with different duct deposition densities. The reference irradiance density was 760 W m^{-2}. It is shown that, the dust has a significantly effect on the short circuit current output. When dust deposition density increased from 0 to 22 g m^{-2}, the I_{sc} reduced from 100% to 78% of its maximum value. Moreover, the tendencies of reduction for three modules are similar to each other. The difference between the cell types is not considerable.

Fig. 8 shows the normalized open circuit voltage $V_{oc}/V_{so\ \mathrm{clean}}$ of different modules for various dust deposition densities. A degradation of the voltage varying the dust weight was also observed, however, the reduction rate was slight. The maximum reduction of V_{oc} is about 6%.

Fig. 9 displays the reductions of energy output efficiency varying the different dust deposition densities. The normalized efficiency reduction was obtained by

$$E_{\mathrm{reduction}}/E_{\mathrm{clean}} = \left(E_{\mathrm{clean}} - E_{\mathrm{dirty}}\right)\Big/E_{\mathrm{clean}} \quad (1)$$

where E_{clean} and E_{dirty} are the output efficiencies of PV module before and after the dust accumulation, respectively.

In this work, the power output efficiency of PV module was estimated by:

$$E = \frac{\text{Output Power}}{\text{Input Sunpower}} = \frac{V_{oc}I_{sc}}{GA} \quad (2)$$

where V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, G is the reference irradiation and A is the area of solar module.

From Fig. 9, it can be observed that when dust deposition density increased from 0 to 22 g m^{-2}, the corresponding reduction of output efficiency grew from 0 to 26%. Dust deposition has an

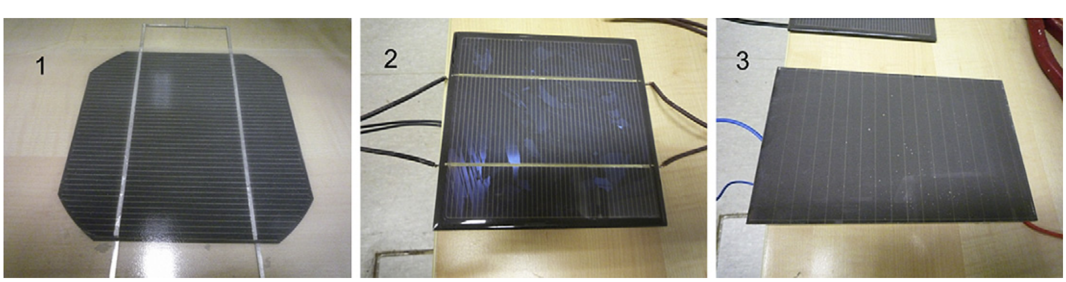

Fig. 4. Photographs of PV modules used in current experiment.

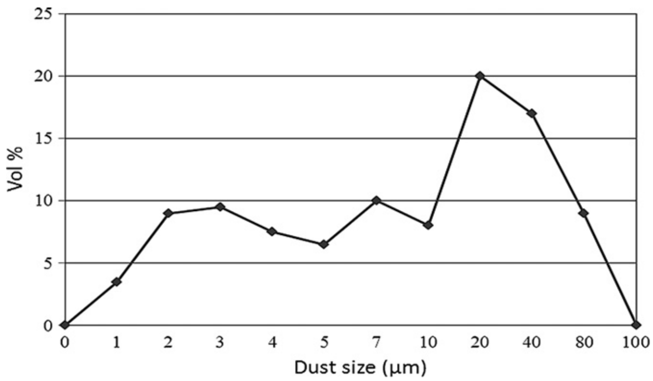

Fig. 5. Dust size distribution by volume percentage.

Table 2
Chemical components of test dust.

Chemical	% of weight	Chemical	% of weight
SiO_2	68–76	CaO	2.0–5.0
Al_2O_3	10–15	MgO	1.0–2.0
Fe_2O_3	2–5	TiO_2	0.5–1.0
Na_2O	2–4	K_2O	2.0–5.0

important influence on the output performance of PV modules. Moreover, the difference of reduction rates between the cell types is not obvious. By fitting the experiment data for the three modules as the dust deposition density, it is found that, the reduction of module efficiency has a linear relationship with the dust deposition density. The reduction of module efficiency has a linear relationship with the dust deposition density:

$$E_{\text{reduction}}/E_{\text{clean}} = k\rho_{\text{depostion}} \tag{3}$$

where k is the fitting factor for modules. It is 0.0139 when fitting all modules together. This trend is observed to be suitable for the three different types of solar modules. For individual modules, the factor k is 0.0115, 0.015 and 0.0139 for module 1, module 2 and module 3,

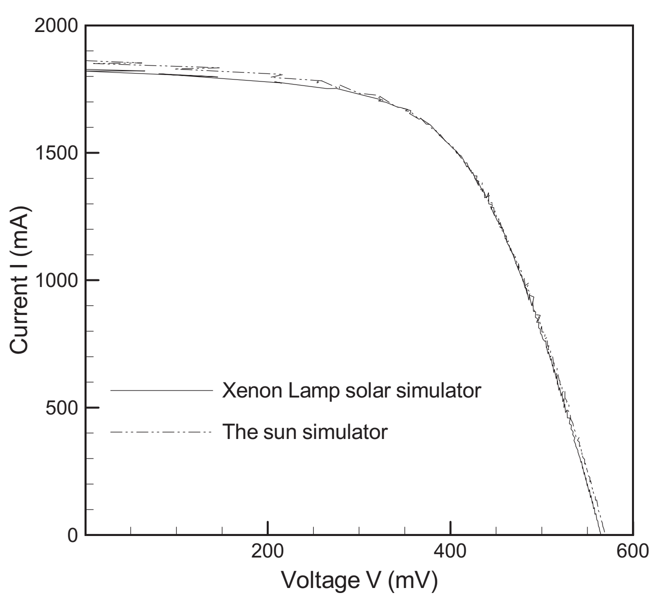

Fig. 6. The comparison of I–V curves measured under different solar simulators (module 1).

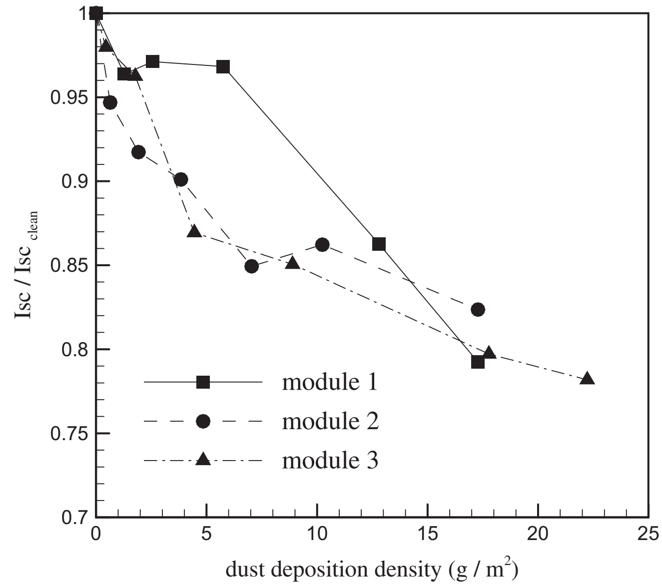

Fig. 7. Variations of short circuit current for different dust deposition densities.

respectively. Although the differences among three modules are not distinct, module 2 shows relatively the highest trend of efficiency reduction and module 1 gives the lowest.

3.3. Effect of solar intensity

When the dust deposition density was fixed, the effect of solar intensity on efficiency degradation was tested. Shown in Fig. 10 are the variations of output efficiency reduction under different solar irradiances when the dust deposition density was fixed at about 8 g m^{-2}. For the solar irradiance varied from 300 W m^{-2} to 760 W m^{-2}, the reduction of output efficiency varied from 4.4% to 11.6%. It is also indicated that, the reductions of output efficiency at relatively lower or higher solar densities are much more severe. This phenomenon is probably attributed to relatively higher reflection effect of the deposited dust to light. At medium solar

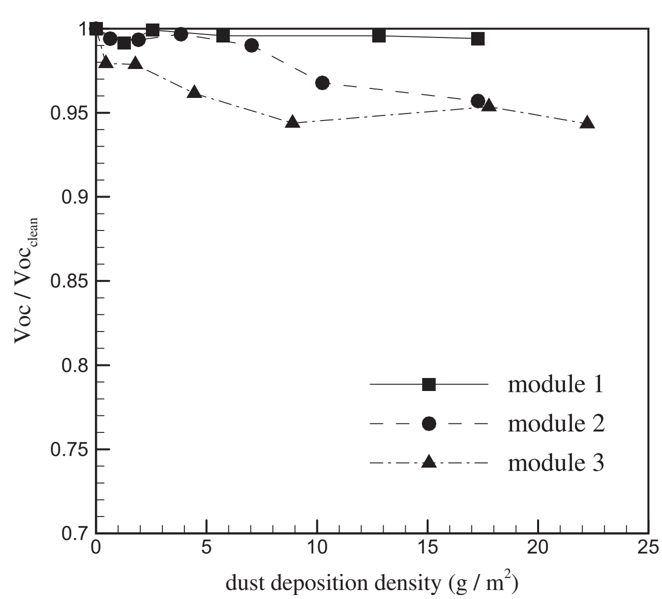

Fig. 8. Variations of open circuit voltage for different dust deposition densities.

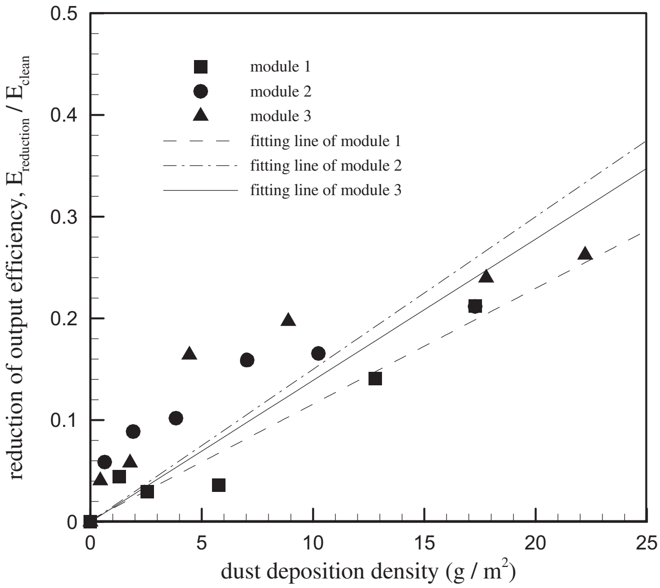

Fig. 9. Variations of output efficiency reduction for different dust deposition density.

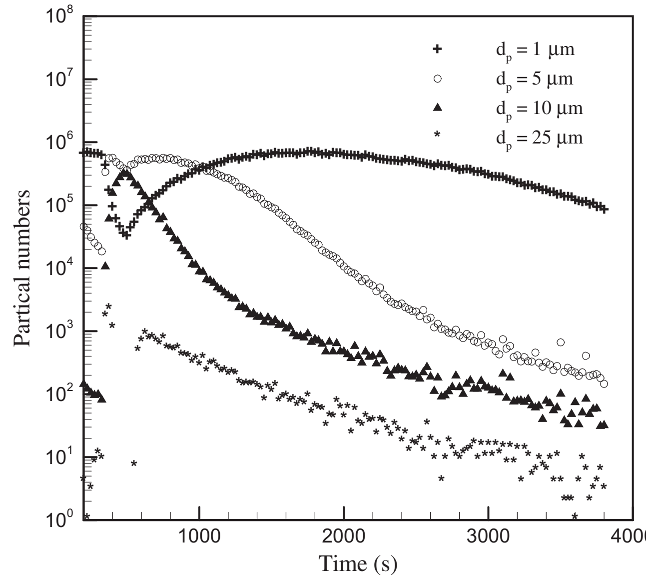

Fig. 11. Development of the dust number concentration varying during 4000 s.

intensity, this effect is weaker and thus efficiency reduction drops in the middle of the trend lines of experimental data.

3.4. *Effect of surface material*

The effect of surface material on dust accumulation and the correspondingly reduction of module efficiency were investigated. In this case, the dust was injected into the chamber at the first 200 seconds (s) and it slowly deposited onto the PV modules. Meanwhile, the *I*–*V* curves of PV modules were measured every 10 min since $T = 0$ s. Fig. 11 displays the development of dust number concentration during 4000 s. Dusts with size around 1 μm, 5 μm, 10 μm and 25 μm were monitored. It can be found that, the developments of dust number concentration were different for different sizes. The concentration of larger dusts decreased faster than the smaller ones.

Fig. 12 shows the module efficiency reduction accordingly as a function of time during 4000 s. It is observed that, the efficiencies of power output reduced quickly in the first 600 s, which was related to the diminution of dust concentration. As shown in Fig. 11, in the first 600 s, the reductions of dust with size around 10 μm and 25 μm were dominating. These two figures indicated that, the degradation of PV module was mostly affected by large particles. At the same time, the degradation speeds were found to be different for the three modules. Module 1 degraded slower than module 3 due to the lower influence of dust deposition onto module 1 with mono-crystalline silicon cell. The efficiency of module 2 degraded faster than the other two modules under the same dust concentration. This behaviour indicates that, module 2 with poly-crystalline silicon cell covered by epoxy surface, accumulates dust more easily compared to other two modules. Although the surfaces are both smooth for glass and epoxy, the surface materials may affect the deposition velocity of airborne dust greatly under the

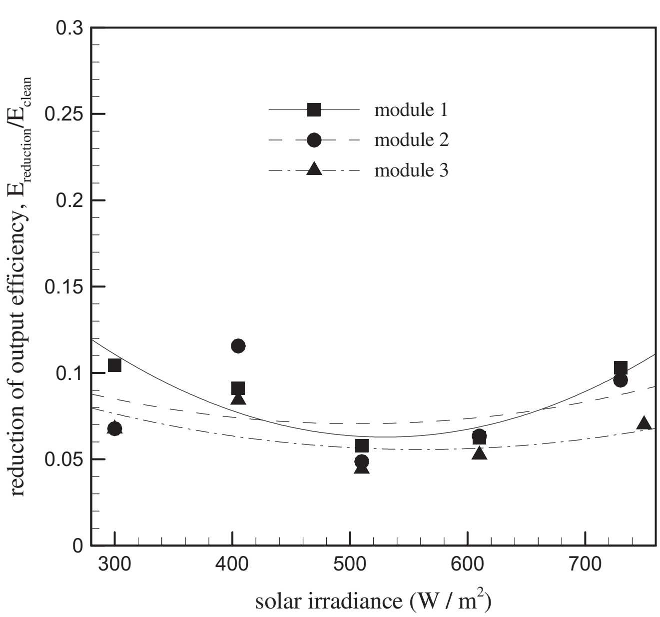

Fig. 10. Variations of output efficiency reduction for different solar irradiances.

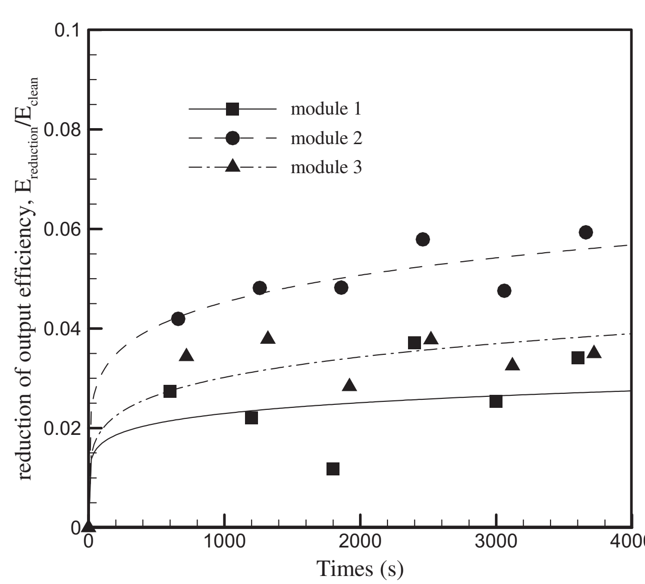

Fig. 12. The reduction of module output efficiency varying with times.

movement of air flow. The reduction trends of output efficiency can be easily observed from the trend lines of all modules, though intermittent fluctuations (say, rises and drops) were also observed but not obvious, as demonstrated in Fig. 12. One group of distinct rise and drop for module 1 at approximately 2000 s time are observed which is probably caused by light refection or experimental error.

4. Conclusions and recommendation

The deposition and accumulation of airborne dust pollution significantly reduce the output performance of PV modules. In this work, laboratory experiments were conducted to study the impact of dust deposition on different types of PV modules. A test chamber was used to access a natural dust deposition process and a solar simulator system was utilized to simulate the sun irradiance. Three different types of solar PV modules were tested and compared. The effects of dust deposition density, the irradiance density and the surface material were investigated. From the experimental results, the following conclusions can be obtained:

1. The deposition and accumulation of airborne dust on solar modules caused a significant degradation of short circuit current. Conversely, the reduction of open circuit voltage was insignificant.
2. In this work, the corresponding reduction of output efficiency grew from 0 to 26% when dust deposition density increased from 0 to 22 g m^{-2}. The reduction of efficiency has a linear relationship with the dust deposition density, and the difference caused by cell types was not obvious.
3. The reductions of output efficiency at lower and higher solar densities were more obvious and severe.
4. The degradation of PV module was mostly affected by large particles. The surface material has a potential influence on the output efficiency reduction. The poly-crystalline silicon cell covered with epoxy surface accumulated more dust than other two cells with white glass surfaces.

To maximize the output of solar PV module and reduce the degradation caused by airborne dust accumulation, frequently cleaning is strongly recommended especially for those drought areas (such as northern west China) and polluted urban areas. The poly-crystalline silicon module covered with epoxy need to be cleaned more often than other cells covered with glass or Tefzel. Furthermore, the selection of module surface material, such as self-cleaning glass, may be helpful to prevent dust deposition and accumulation, and enhance the module power performance.

In addition, as we know, the most important parameters that determine the operating conditions of a solar cell are the total irradiance, the spectral distribution of the irradiance and the temperature. However, because of the difficulty to obtain spectral measurements, the effect of changes in spectral distribution on the short circuit current and efficiency of different types of solar cells were not considered in this work. Further study on this issue is strongly recommended. Furthermore, improvement experimental work considering other factors, such as the tilt angle of the modules and air movement, are suggested.

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