# INVESTIGATING THE EFFECT OF TEMPERATURE DIFFERENCES AND GENERATED CURRENT ON DUST ACCUMULATION PROCESS ON SOLAR PHTOVOLTAIC (PV) MODULES

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# INVESTIGATING THE EFFECT OF TEMPERATURE DIFFERENCES AND GENERATED CURRENT ON DUST ACCUMULATION PROCESS ON SOLAR PHTOVOLTAIC (PV) MODULES

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**A thesis submitted in partial fulfillment of the requirements**

**for the degree of Doctor of Philosophy**

August 2017

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______________ (Signed)

JIANG YU (Name of student)

# ABSTRACT


| | |
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| Abstract of thesis entitled: | Investigating the effect of temperature differences and generated current on dust accumulation process on solar photovoltaic (PV) modules |
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Solar Photovoltaic (PV) technology, can directly convert solar energy into utilized electricity with the help of photovoltaic effect by semi-conductor materials. Solar PV modules mainly contain solar cells that can convert receiving solar energy into electricity, glass covers to provide protection for vulnerable solar cell units and other electrical components to transform generated current meet the energy requirements of consumers. Many environmental parameters can greatly affect the energy conversion efficiency of solar PV modules, such as solar irradiance and temperature of solar cells. Additionally, another environmental parameter, dust accumulation, which means that airborne dust from the atmosphere air deposits on solar PV module covers due to different forces, is a significant issue when engineers considering the energy performance of solar PV modules because the accumulated dust can greatly reduce the received solar radiation and affect the energy conversion efficiency of solar PV modules. The formation of accumulated dust is inevitable because solar PV plants are generally located in areas where sunlight is not only abundant for energy conversion process but

also has a high concentration of dust particles for dust accumulation. Based on previous studies all over the world, the effect of dust on solar PV modules is significantly negative due to the reduction in received solar irradiation by the refraction and extinction process of deposited dust particles. There are some researches on the dust accumulation on solar PV modules, but mainly focusing on the impact of dust density and property or environmental parameters such as wind and exposure time on the energy performance of solar PV modules without examining the impact of the operating solar PV modules on the dust accumulation process.

During sunshine days, when the operating solar PV modules receives solar radiation and converts some irradiance into electricity with efficiency generally lower than 20%, the most received solar radiation will be converted into heat, which results in high temperature of solar cells, especially with high solar irradiance. This will cause obvious temperature difference between solar module surface and its surrounding air. In addition, the generated current by solar PV modules will cause electric field. Both the temperature difference between module surface and ambient air and the generated electric field will affect the particle deposition onto module surface. So, it is significant to study the effect of operational solar PV modules on the surface dust accumulation process. In addition, considering the greatly negative effect of dust accumulation on the energy conversion performance of solar PV modules, studies of approaches for removing or stopping dust accumulation thus have received lots of attention. Even though some studies reported the methods for cleaning or preventing dust accumulation on solar PV modules to maintain the high energy conversion efficiency of solar cells, but not the significant issue of cleaning frequency for cleaning solar PV modules with dust particles, especially for desert areas.

Therefore, this work aims to study the effect of characteristics of operating solar PV modules, both temperature differences and generated current, and to investigate cleaning issues, including cleaning frequency and wind cleaning process.

Firstly, this thesis investigates the influence of temperature differences between the PV module surface and the ambient air on dust accumulation process by particle deposition experiments with glass samples and solar PV module samples. The measured deposition densities of fine aerosols are from 0.05 to 0.19 $g/m^2$ under the experimental conditions and the glass light transmittance ratios increase with the increase in temperature differences and tilt angles, ranging from 0.975 to 0.996. The glass with higher surface temperature has lower particle density due to the effect of thermophoresis arising from temperature differences. In addition, the deposition densities decrease with the increase of sample tilt angles for all conditions due to the combination effect of aerosol gravity and aerosol surface adhesion. The output power ratios of the PV module samples increase from 0.861 to 0.965 with an increase in temperature difference from 0 to 50 °C, and dust particles have a significant impact on the short circuit current and the output power. However, the influence of particle on the open circuit voltage can be negligible.

Secondly, the effect of generated current on dust accumulation process is illustrated. Based on the particle deposition experiments for glass samples with different provided currents, it can be found that the generated current can greatly increase the dust accumulation density due to the electrostatic force by the generated electric field because of the generated current. Particle deposition density results have strongly verified the attractive effect by the generated current. In addition, the influence of different mechanisms for electrostatic force on particle deposition process is analysed, including Columbic force and image force. Columbic force plays a significant role in particle deposition process on the operating solar PV modules and the impact of image force can be neglected. The calculated particle deposition velocity due to Columbic force under strong electric field based on Eq. (4.1) ranges from $7.34\times10^{-7}$ m/s to $3.12\times10^{-4}$ m/s for different particle diameters. When particle diameters increase from 0.01 μm to 0.5 μm, deposition velocity decreased nearly 75% from $3.12\times10^{-5}$ m/s to $7.34\times10^{-6}$ m/s because small particle is significantly influenced by Columbic force when compared with large particle in this size range. However, when particle diameters increase from 0.5 μm to 10 μm, the deposition velocity due to electric field is greatly increased 100% from $7.34\times10^{-6}$ m/s to $1.51\times10^{-5}$ m/s because large charging numbers for large particles. Deposition velocity of image force is increased with the increase of particle diameters because deposition velocity of image force is proportional to the particle charge level and large particles have large particle charging number based on diffusion charging mechanism. In addition, the deposition velocity also increases with the increase of dielectric constant.

Thirdly, a resuspension model for rough and spherical particles detaching flat surface is firstly developed to analyse the cleaning effect of wind on the accumulated dust particles on solar PV modules. This model considers adhesion force, hydrodynamic force and torque. The minimum shear velocity and corresponding actual wind velocity for particle removal are calculated for particles with diameters ranging from 0.1 μm to 100 μm based on this model. It is found that large particles could be effectively cleaned by wind due to the low required resuspension velocity compared with small particles. The minimum required shear velocity for particle resuspension process are found to range from 0.23 m/s to 57.56 m/s for different particle sizes, and increases with the increase of particle diameter and the actual wind velocity vary from 0.82 m/s to 2219.8 m/s, and the ratios of shear velocity to wind velocity range 0.04 to 0.06. Therefore, these findings can verify that particle resuspension method is a significant way to analyse the wind cleaning process on deposited particles. In addition, considering the cleaning process of wind, more accurate model to estimate energy output for solar PV modules due to the accumulated dust can be developed for solar energy industry.

Finally, a novel method to estimate the cleaning frequency for dirty solar PV modules in desert areas has been established based on the existing particle deposition velocity model. The environmental parameters used are 20 μm for representative average diameter, $0^{o}$ for tilt angle (horizontal position) and 100 $\mu g/m^3$ for particle concentration in the ambient air respectively. In addition, the cleaning criterion is 5% reduction in power with accumulated dust density of 2 $g/m^2$. The cleaning frequency for solar PV modules in desert regions is about 20 days. Therefore, it's recommended that the PV modules cleaning can be determined as three weeks to keep the high power output. In addition, the calculated cleaning time based on the present model agrees well with the related experimental results. Therefore, this verified method can be adopted in engineering application to estimate the cleaning frequency of dirty PV modules. Additionally, the average particle diameters and tilt angles can significantly influence the required cleaning time because the deposition velocity is highly dependent on gravity. The cleaning time is decreased to 20 days from 6256 days with the increase of representative average diameter from 1 μm to 20 μm and, is increased to 78.2 days from 20.2 days with the increase of the inclined angle from 0 degree to 75 degree, respectively.

In summary, the impact of temperature differences and generated current on dust accumulation process on solar PV modules and cleaning issues (wind cleaning process and cleaning frequency for desert areas) are newly investigated. The main academic contributions of this thesis can be presented as follows: 1) existing temperature differences between module surface and ambient air can greatly decrease the dust accumulation density and thus improve the energy conversion efficiency of solar PV modules; 2) the generated current can significantly increase the dust accumulation density and thus decrease the energy output power of solar PV modules; 3) a novel method to calculate the cleaning frequency for desert areas is developed based on particle deposition velocity model; 4) the method for evaluate the performance of wind cleaning process for dust accumulation is established based on particle resuspension theory.

# PUBLICATIONS DURING PHD STUDY

## Journal papers:

Jiang, Yu, Lin Lu. “Analysing influence of generated current and corresponding electrostatic force on dust accumulation process on flat solar photovoltaic (PV) module surfaces”. (To be submitted).

Jiang, Yu, Lin Lu. “Analysing effect of temperature differences and corresponding thermophoresis on dust accumulation process on solar photovoltaic (PV) module surfaces.” Solar Energy (To be submitted).

Jiang, Yu, Lin Lu, A. R. Ferro, G. Ahmadi. “Analyzing wind cleaning process on the accumulated dust on solar photovoltaic (PV) modules on flat surfaces.” Solar Energy 159 (2018): 1031-1036

Jiang, Yu, Lin Lu, Hao Lu. "A novel model to estimate the cleaning frequency for dirty solar photovoltaic (PV) modules in desert environment." Solar Energy 140 (2016): 236-240.

Jiang, Yu, Lin Lu. "Experimentally Investigating the Effect of Temperature Differences in the Particle Deposition Process on Solar Photovoltaic (PV) Modules." Sustainability 8.11 (2016): 1091.

Jiang, Yu, Lin Lu. "A study of dust accumulating process on solar photovoltaic modules with different surface temperatures." Energy Procedia 75 (2015): 337-342.

Sun, Ke, Lin Lu, Yu Jiang. "Analysis of orientation and tensor properties of airborne fibrous particle flow." International Journal of Numerical Methods for Heat & Fluid Flow 24.8 (2014): 1795-1802.

Qi, Ronghui, Lin Lu, Yu Jiang. "Investigation on the liquid contact angle and its influence for liquid desiccant dehumidification system." International Journal of Heat and Mass Transfer 88 (2015): 210-217.

Lu, Hao, Lin Lu, Yu Jiang. "Numerical simulation of particle deposition in duct air flows with uniform, expanding or contracting cross-section." Energy and Buildings 128 (2016): 867-875.

Lu, Hao, Lin Lu, Yu Jiang. "Numerical study of monodispersed particle deposition rates in variable-section ducts with different expanding or contracting ratios." Applied Thermal Engineering 110 (2017): 150-161.

## Conference papers:

Yu Jiang, Lin Lu and Ke Sun. Simulation of the PM2.5 Dust Deposition on Self-Cleaning Glasses. 12th International Conference on Sustainable Energy Technologies, 2013. Hong Kong, China.

Yu Jiang, Lin Lu. Study of different self-cleaning technologies in reducing particle deposition under dry environment. The 13th International Conference on Indoor Air Quality and Climate, 2014. Hong Kong, China.

Yu Jiang, Lin Lu. A study of dust accumulating process on solar photovoltaic modules with different surface temperatures. The 7th International Conference on Applied Energy, 2015, Abu Dhabi, United Arab Emirates

Yu Jiang, Lu Lin. A novel way to calculate the light transmittance loss of glass for Photovoltaic (PV) modules according to known accumulated dust density. The 14th International Conference on Sustainable Energy Technologies, 2015 Nottingham, UK

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# NOMENCLATURE

## Abbreviations

| | |
|---|---|
| CFD | Computational Fluid Dynamics |
| CSP | Concentrated Solar Power |
| DC | Direct Current |
| PV | Photovoltaic |

## Ordinary Symbols

| | | |
|---|---|---|
| $C$ | Particle concentration | (g m$^{-3}$) |
| $D$ | Particle Brownian diffusivity | |
| $d_p$ | Particle diameter | (μm) |
| $C_c$ | Cunningham coefficient | |
| $E$ | Electric field intensity | (V m$^{-1}$) |
| $f$ | Drag coefficient | |
| $H$ | Thermophoretic force coefficient | |
| $J$ | Particle flux | (g) |
| $k_a$ | Air thermal conductivity | (W m$^{-1}$ K$^{-1}$) |
| $k_p$ | Particle thermal conductivity | (W m$^{-1}$ K$^{-1}$) |
| $m$ | Deposition density | (g m$^{-2}$) |
| $n$ | Particle charging number | |
| $P_A$ | Output power of dirty PV module | (W) |
| $P_C$ | Output power of a clean PV module | (W) |

| | | |
|---|---|---|
| $V_t$ | Deposition velocity of turbophoresis | (m $s^{-1}$) |
| $V_{th}$ | Deposition velocity of thermophoretic force | (m $s^{-1}$) |

## Greek symbols

| | | |
|---|---|---|
| $\varepsilon$ | Dielectric constant | |
| $\tau$ | Shear stress | |
| $\mu$ | Dynamic viscosity | (Pa s) |
| $\rho$ | Density | (g $m^{-3}$) |

# CHAPTER 1 INTRODUCTION

With the rapid development of modern society, the energy requirement to support this rapid expansion is drastically increasing. Up to now traditional fossil fuels are still playing significant roles in satisfying the tremendous energy requirement as last century (Tyagi, Rahim, Rahim, & Selvaraj, 2013). However, the utilization of fossil fuels can lead to obvious and serious environmental problems, such as global warming due to carbon dioxide from the combustion process of coals or oil and pollutions to water resource because of exploitation of fossil fuels or emission of waste heat from thermal power plants. In order to protect the environment and deal with the pollution problem, solar energy, as a kind of renewable energy, has been widely used all over the world in recent years.

Generally speaking, heat, electricity and chemical energy can be provided by various solar energy systems which can convert the received solar radiation into different types of utilized energy above (Tyagi et al., 2013). The most common way to use solar energy is that converting this renewable energy into usable electrical power for consumers or industries directly. Currently, there are two main ways of generating electricity from solar energy: one is concentrated solar power (CSP) technology, and the other one is solar photovoltaic (PV) technology, as shown in Figure 1.1. CSP technology means making use of solar collectors to concentrate and collect solar energy for providing high temperature steam to drive the turbines to generate electric power. Compared with solar PV technologies, CSP has an obvious disadvantage. The structure of CSP plant is complicated, so the initial investment is extremely high and large area is needed when CSP plants are built.

(a)

(b)

Figure 1.1 Solar photovoltaic (PV) module (a) and CSP system (b).

## 1.1 Background of solar photovoltaic (PV) technology

Solar photovoltaic (PV) technology, can directly convert solar energy into utilized electricity with the help of photovoltaic effect by numerous semi-conductor materials. PV modules mainly contain solar cells that can convert receiving solar energy into electricity, glass covers to provide protection for vulnerable solar cell units and other electrical components to transform generated current to meet the energy requirements of consumers, as shown in Figure 1.2.

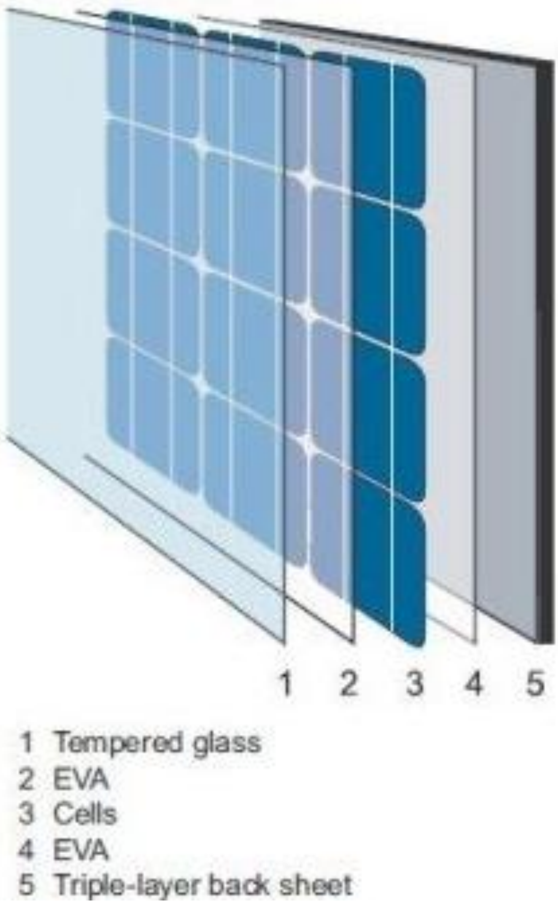



Figure 1.2 Common structure of commercial solar PV modules.

A large number of materials can be used for solar cell production because of their strong ability of converting solar incident light into electricity, and the efficiency of different kinds of solar cells can be seen in Figure 1.3. Due to its high efficiency and easier to be obtained from earth, crystalline silicon has been commonly used in PV industry. Even though its highest power efficiency in laboratory can be higher than 20%, for commercial application, the efficiency of monocrystalline silicon solar cells is usually between 15%-18%. In addition to monocrystalline silicon, polycrystalline silicon is another conventional silicon material for solar cells. Compared with traditional monocrystalline silicon material, the quality of polycrystalline silicon is higher due to lower flaws in structure, but its efficiency is relatively lower (Manna & Mahajan, 2007).

Gallium arsenide (GaAs) solar cell is a kind of compound semiconductor with similar structure to silicon. Compared with conventional silicon solar cells, GaAs solar cells have high efficiency because the low band gap energy with thin thickness (Deb, 1998). So, GaAs solar cells are extensively used in concentrator PV modules because of these two advantages.

In addition to crystalline solar cells, thin film materials have also been receiving lots of attention owing to the advantage of low cost in the production process. In general, the thickness of solar cells with thin film technology normally is less than 300nm (Vrielink, Tiggelaar, Gardeniers, & Lefferts, 2012). Amorphous silicon plays important role in thin film solar cells because of its higher efficiency. Besides, compared with monocrystalline silicon, amorphous silicon has a higher light absorptivity due to its random crystalline structure. However, the high band gap from disordered structure results in the reduction in conversion efficiency compared to monocrystalline silicon solar cells.

Recently, some organic compounds are potential materials to replace traditional silicon materials due to the industry interest in reducing cost. However, the energy conversion efficiency is extremely low and more work need to do to make it application in the future.

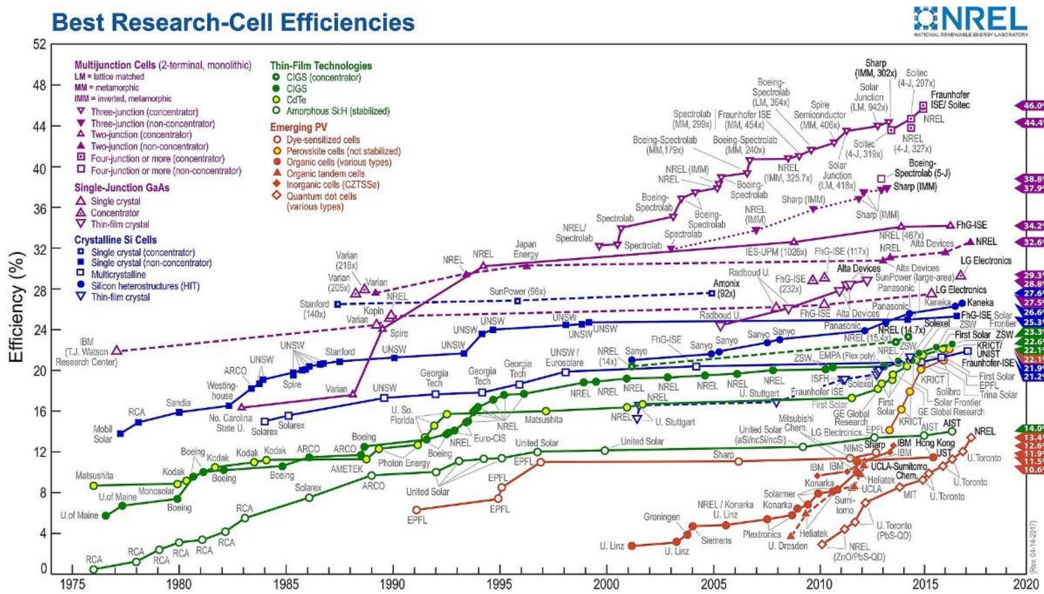



Figure 1.3 Efficiency of different kinds of solar cells under standard conditions (National Renewable Energy Laboratory Research Cell Record Efficiency Chart in 2017).

The energy performance of PV modules is obviously influenced by various environmental parameters. The first one is the solar irradiance. There is no doubt that the output power of PV modules is increasing with the increase of solar light intensity because the more number of photons can be received by solar cell units. In details, the short circuit current rapidly increased with the increase of solar irradiance. However, the open circuit voltage of solar cells is nearly unchanged. The change of weather can also affect the continuity of solar PV module power output because received solar irradiance is constantly changing. Another significant parameter is the temperature of solar cells. Generally speaking, the increase of temperature can greatly decrease the energy converting efficiency of solar cells because the band gap increases with the temperature and open circuit voltage thus decreases. For different solar cell materials, monocrystalline silicon has the greatest temperature influence and the influence is relatively small for polycrystalline silicon and thin film solar cells. Based on the influence of temperature on PV modules, cooling methods are significant for engineers to maintain the high energy efficiency for practical operation. So, considering the reduced impact of temperature on solar cells, the efficiency of PV modules is increased with the increase of wind velocity because high wind velocity can effectively transport the generated heat and thus cooling solar cells with high temperature to keep the efficiency.

In addition to these parameters introduced above, dust accumulation, another common phenomenon in nature, can significantly decrease the power output of solar PV modules because the solar incident light can be blocked by dust particles. This phenomenon will be introduced in next two sections.

## 1.2 Dust deposition in nature

As discussed in previous section, dust accumulation can greatly affect the power output performance of solar PV modules owing to decreased effect on received solar light by accumulated particles. Actually, dusts generally mean solid particles which diameters are less than 500mm (Sarver, Al-Qaraghuli, & Kazmerski, 2013). Airborne dusts can result from various sources, such as the matter from the eruption of volcano, particles from transportation, soil particulates re-suspended into the atmosphere due to wind and the waste from many factories. Therefore, the size distributions, shapes, electrical properties or other physical properties and chemical compositions of airborne dusts vary for different regions because of various sources and generation mechanisms (Sarver et al., 2013).

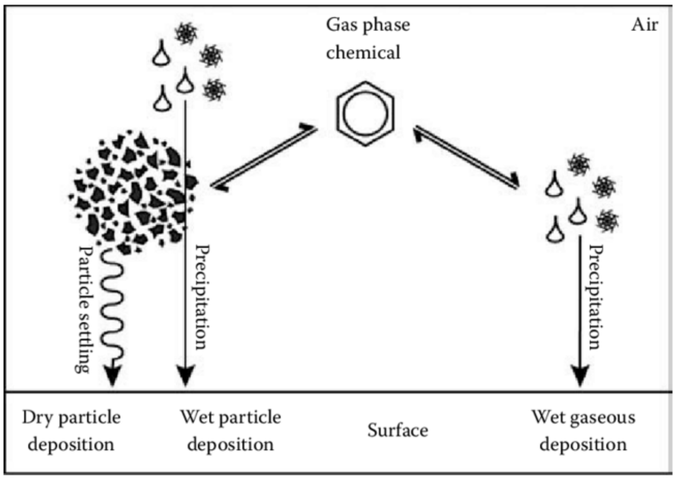



Figure 1.4 Pathways for dry particle deposition, wet particle deposition, and wet gaseous deposition of chemical contaminants from the atmosphere to the surface (MacLeod et al., 2010).

Airborne dust particles can deposit onto object surface when they flow through the surface from different pathways, including dry deposition and wet deposition, as presented in Figure 1.4. Therefore, dust particle deposition is a common phenomenon all over the world and greatly influences the deposited surface, indoor environment and health of human beings. Firstly, particle deposition can happen onto air duct surface in ventilation and therefore change the size distribution of dust particles. In addition, deposited particles onto duct surface can be re-suspended into the indoor environment via sufficient air flow and contributes to the negative effect on the health of building occupants (Zhao & Wu, 2006b). Secondly, particle can deposit onto exposed skin surface and result in adverse impact on people. For instance, airborne particles can carry various semivolatile organic compounds (SCVOs) due to the low vapor pressure and this kind of air pollutants has been verified that it can increase the risk of cancer and other severe health problems (Shi & Zhao, 2013). In addition, dust particles can deposit onto aircraft engine compressors and decrease the performance of compressors because deposited particles can dramatically deteriorate the structure of compressors and thus has adverse effect on energy behaviour of compressors (Döring, Staudacher, Koch, & Weißschuh, 2017).

Additionally, there are several kinds of mechanisms which play important roles in particle deposition process, including gravity settling, Brownian diffusion, turbulent diffusion and turbophoresis (Zhao & Wu, 2006a). Firstly, for the gravity settling, the deposition of this mechanism mainly depends on the size, density and shape of particles and the effect of compositions can be ignored (Sarver et al., 2013). Secondly, for the Brownian diffusion, small particles are greatly influenced by this mechanism and the irregular movement will be generated from this mechanism because the unbalance of all directions (Sarver et al., 2013). Then the turbulent diffusion is mainly taking particles to the surface that is exactly opposite to the effect of Brownian diffusion. Finally, turbophoresis is the result of the gradient in turbulent velocity intensity due to the inhomogeneous of turbulence in turbulent flow and is significant for particles which have large inertia and near the wall areas (Zhao & Wu, 2006a).

So, to model the deposition velocity in order to quantify the influence of dust deposition process on different surface, a three-layer particle deposition model has been built (Lai & Nazaroff, 2000) and this model can accurately predict the velocity of particle deposition under turbulent flow, as shown in Eq. (1.1).

$$J = -\left(\varepsilon_p + D\right)\frac{\partial C}{\partial y} - i v_s C \tag{1.1}$$

where $J$ is the particle flux to the surface. $D$ is the particle Brownian diffusivity in the boundary layer, $\varepsilon_p$ is the eddy diffusivity of particles in the boundary layer, $i$ means the orientation of the surface and $v_s$ is the settling velocity of particles.

Additionally, experimental study of particle deposition velocity is important for validation of theoretical results. For direct measurement, the fluorescence spectroscopy method is the most common method to measure the particle deposition velocity. But the weakness of fluorescence spectroscopy method is obvious. The first one is that deposited particles can be removed from the tested surface by other environmental parameters. The other one is that the spatial distribution of deposited particles can't be obtained. For indirect measurement, the particle deposition velocity is generally calculated by measuring particle concentrations of the upstream and downstream. Compared with the direct measurement, the indirect measurement techniques are not as accurate as direct measurement in measuring particle deposition velocity because the sensitivity of measurement components and the disturbances of airflow (Piskunov, 2009).

Considering the difficulty of experimental studies, numerical simulation method has become the most significant method to investigate particle deposition process in turbulent flow because the details of particle deposition process such as the field of turbulent and the path of particle movements can be easily and quickly calculated with sufficient accuracy (Q. Chen, 2009; Lecrivain, Sevan, Thomas, & Hampel, 2014).

## 1.3 Dust accumulation on solar PV modules

Additionally, dust accumulation, which means that airborne dust from the atmosphere air deposits on solar PV module covers due to mechanisms introduced above, is a significant issue when engineers considering the energy performance of PV modules because dust accumulation can dramatically affect the energy conversion behaviour of PV modules. A typical comparison of energy output of clean PV module and the same module with four-weeks dust accumulation is shown in Figure 1.5 and

Figure 1.6 (Ramli et al., 2016). The formation of dust accumulation for solar PV modules is inevitable because solar PV plants are generally located in areas where sunlight is not only abundant for energy conversion process but also has a high concentration of dust particles for dust accumulation. Based on previous studies all over the world, the effect of dust on PV modules is negative due to the reduction in received solar irradiation by the refraction and extinction process of deposited dust particles (Costa, Diniz, & Kazmerski, 2016; Z. A. Darwish, H. A. Kazem, K. Sopian, M. A. Al-Goul, & H. Alawadhi, 2015b; Maghami et al., 2016; Sarver et al., 2013; Sayyah, Horenstein, & Mazumder, 2014). There are many researchers who have focused on the dust accumulation on PV modules since the last century (Mani & Pillai, 2010). For example, in 2013, Touati et al. found that the reduction was 10% after a 100-day outdoor experiment in Qatar and El-Din et al. presented that the average reduction in power output of thin film PV modules in Alexandria during a 2-month observation due to dust particles was 9.86% (ElDin, Abel-Rahman, Ali, & Ookawara, 2013; Touati, Massoud, Hamad, & Saeed, 2013). In addition to obvious and observed adverse impact of dust accumulation on energy conversion performance of PV modules, the effect of partial environmental parameters on dust accumulation has been investigated. For instance, larger inclined angles of PV modules can reduce the dust deposition and thus maintain higher energy output in comparison with lower tilt angle position (Elminir et al., 2006; Mejia & Kleissl, 2013). Additionally, wind directions can significantly affect the velocity of dust accumulation and wind velocity can increase the density of dust accumulation (Goossens, Offer, & Zangvil, 1993; Goossens & Van Kerschaever, 1999).

Researchers have only investigated the impact of dust density and property or environmental parameters such as wind and exposure time on the energy performance of PV modules. However, their studies neglected the impact of operational PV modules on the dust accumulation process. The first property of operational PV modules is the temperature differences between PV module surface and the ambient air because most received energy of solar radiation cannot be converted into electricity, only changed into heat and thus increase the surface temperature of PV modules. This temperature difference can result in temperature gradient and affect deposition velocity of dust particles. The other one is the induced electrical field due to the generated current based on photovoltaic effect of solar cells in PV modules. This induced electrical field may also affect dust deposition velocity. So, it is significant to study the effect of the properties of operational PV modules on dust accumulation process to comprehensively evaluate the negative impact of dust accumulation on PV modules by considering the velocity of accumulation process.

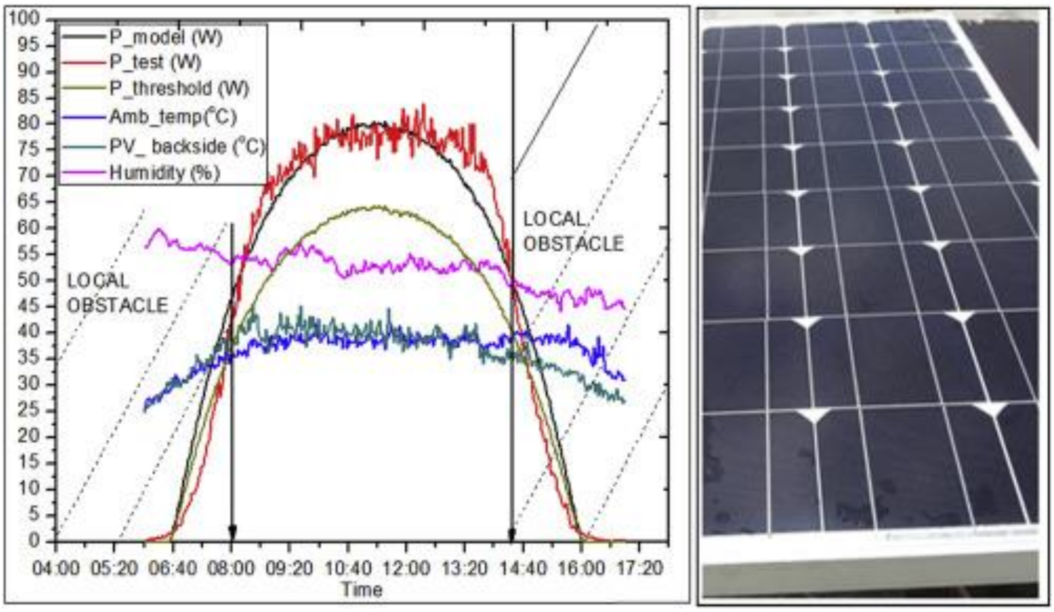



Figure 1.5 Output power of clean PV module (Ramli et al., 2016).

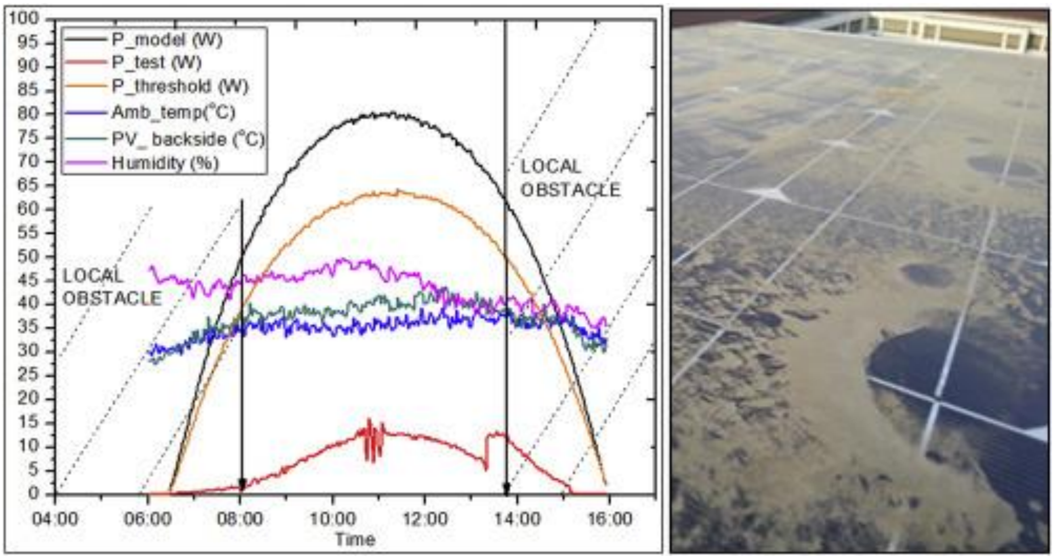



Figure 1.6 Dust accumulation on PV module surface and PV output power after four weeks of dust accumulation (Ramli et al., 2016).

In addition to the influence of environmental parameters on dust accumulation process, to reduce the negative effect of dust particles, researchers have developed new methods or designed novel systems to decrease the total deposition density of accumulated dust (Sarver et al., 2013). One common way is coating chemical coatings, such as super-hydrophilic self-cleaning coating. This coating can effectively remove accumulated dust particles from deposited surface with the help of sufficient rainwater. Besides, electrical cleaning systems have been designed and verified the active cleaning effect on deposited particles in field experiments (Malay Mazumder et al., 2013). But the details of wind cleaning process for accumulated dust particles are not clear even though the cleaning effect of wind has been observed. In addition, the reasonable frequency based on mathematical method for cleaning plan is not reported. So, it is important to develop mathematical method to investigate the natural cleaning process for dust accumulation on PV modules and calculate the cleaning frequency for engineers to design reasonable cleaning design in order to maintain the energy conversion behaviour of PV modules by eliminating the adverse effect of dust particles.

## 1.4 Aims and Objectives

As discussed above, considering the possible decreased effect of dust accumulation on solar irradiance, most of previous researches mainly report the negative effect due to dust particles on the energy conversion performance of solar PV modules, but the study on the influence of operating solar PV modules on dust accumulation process is limited. When a solar PV module operates to generate electricity under strong solar irradiance, its surface temperature is much higher than its ambient air because much received solar energy is converted into heat, not electricity. Peng et al. proved that the temperature difference is existing in different kinds of commercial solar PV modules (Peng, Lu, Yang, & Han, 2013). So, it indicates that there is an existing temperature difference between PV modules and the ambient air because of the strong capture of solar light by PV modules and limited conversion efficiency of solar cells. For dust accumulation process on the module surface, the existing temperature difference may result in capricious effect, which needs to be systematically investigated.

In addition to temperature differences due to operating solar PV modules, when PV modules generating electricity under sufficient solar radiation, the transportation of generated current may lead to electric fields near the glass cover. This generated electric field can affect the velocity of dust accumulation on PV modules and thus decrease the conversion efficiency of PV modules due to possible increases in dust accumulation density. However, the effect of this generated current on dust accumulation process for PV modules is not reported yet and needs to be further studied for the development of mathematical models with high accuracy to estimate the energy conversion performance of PV modules considering the decreased influence because of dust accumulation.

In addition to the influence of properties of operational PV modules on dust accumulation process, rainfall and wind are the typical natural cleaning processes. Water is an effective cleaning agent for removing accumulated dust particles from PV covers; therefore, rainfall in sufficient amount could restore the initial performance of PV modules. But, in many desert areas, the amount of rain is very low for effective removing dust particles. Besides, for the cleaning process by wind, limited research is conducted to investigate this natural phenomenon. The details of the effect of various dust particle sizes and compositions and the required wind velocity for effective cleaning are unclear; therefore, estimating the wind effect on cleaning the accumulated dust from PV module surface is a worthwhile study.

Finally, considering the importance of cleaning the dirty or polluted PV module covers, it is obvious that cleaning issues in desert environment where water resource is scarce have to be considered to minimize the cleaning cycles at a reasonable level for maintaining the system performance (Khonkar et al., 2014). However, research on cleaning frequency of dusts on the PV modules is also limited. Therefore, proposing a theoretical model based on the dust deposition velocity calculation to recommend the frequency for cleaning dirty PV modules in desert environment is significant for engineers.

In conclusion, research of dust accumulation process on operating solar PV modules is limited, and the issues for reasonable cleaning frequency and the cleaning influence of wind on accumulated dust on PV module covers need to be investigated.

Based on the previous discussions, the main objectives of this thesis are listed as follows:

1) To experimentally study the influence of temperature difference between PV modules cover and the ambient air due to the heat absorption on dust accumulation

process on PV module covers. To fully investigate the performance of energy conversion process of actual PV module samples in addition to the direct dust deposition density with different temperature differences.

2) To investigate the effect of generated currents on dust accumulation process on glass module surface and to analyse the results of dust deposition density and transmittance ratios in order to point out the reason and to build the model to examine the influence.

3) To build a particle resuspension model to evaluate the minimum shear velocity (and the corresponding actual wind velocity) and to qualitatively analysed the difficulty of different compositions of deposited dust for removal.

4) To develop a novel method for calculating the accumulated velocity of dust on PV modules and to estimate the module cleaning frequency for the desert environment. The influence of different parameters on calculated cleaning frequency are discussed.

## 1.5 Organization of This Thesis

In Chapter 1, the background of solar PV modules is introduced and the environmental parameters for the energy performance of PV modules are discussed. In addition, dust deposition process in nature is introduced by different aspects, such as deposited mechanisms and model for calculating deposition velocity. Besides, considering a special particle deposition process, dust accumulation on solar PV module surface, degradation impact of dust accumulation on energy conversion performance PV module performance is briefly introduced and the influence of environmental parameters on this phenomenon is summarized. Finally, the research gaps and the aims of this thesis are also provided.

Chapter 2 presents a comprehensive and systematically literature review based on the previous studies of this thesis. The influence of dust compositions and sizes, wind and installed tilt angles on dust accumulation are discussed. In addition, the common approaches to deal with dust accumulation issues are presented. Besides, previous research on dust deposition process and dust resuspension process are reviewed respectively, especially on dust deposition velocity and resuspension velocity. The basic flowchart of the research method for this thesis are provided in the last section.

In Chapter 3, the influence of temperature differences between PV module cover and ambient air on dust accumulation process is analysed based on dust deposition experiments in lab. The model for the deposition velocity due to the temperature difference is analysed. In addition to dust deposition density results, the data of power performance for actual module samples, such as short circuit current and open circuit voltage, are summarized in this chapter.

Chapter 4 presents the study of the effect of generated current on dust accumulation process on PV modules. The relationship between the generated current and dust accumulation density is analysed. Additionally, the results of glass transmittance ratios are measured.

Chapter 5 presents the method for analysing the wind cleaning process of the accumulated dust particles deposited on PV module surfaces. The required shear velocity and the actual wind velocity for resuspension of particles with diameter ranging from 0.1 to 100 μm are evaluated. The effect of particle size and composition on the required removal velocity is also analysed.

In Chapter 6, a novel model to estimate the cleaning frequency is developed for dirty PV modules in desert areas based on the dust deposition velocity and the relationship between deposited dust density and PV module power performance. Based on this model, module cleaning frequency for desert regions is estimated. In addition, the effects of accumulation density, average particle diameters, tilt angles and wind velocity on the cleaning frequency are discussed and analysed respectively.

Finally, Chapter 7 summarizes the main findings of this thesis with the basic ideas for future work. It is sure that the conclusions of this thesis can help readers for better understanding the dust accumulation process on PV modules and help engineers to obtain effective cleaning design in order to maintain the high energy conversion performance of PV modules in solar PV plants.

# CHAPTER 2

# LITTERATURE REVIEW AND RESEARCH METHOD

## 2.1 Introduction

The research on the effect of dust accumulation on solar PV modules has been undertaken for more than seventy years (Mani & Pillai, 2010). In general, it can be divided into two stages. Before 1990s, researchers primarily investigated the power loss of solar PV systems due to dust accumulation in different areas. After 1990s, considering the limitations of previous work, such as the lack of knowledge of accumulated dust particle properties, influence of environmental factors on dust accumulation density and approaches for cleaning or preventing dust accumulation on solar PV modules, researchers started to carry out indoor laboratory experiments with outdoor measurements of field studies to obtain deeper results in dust accumulation process.

So, a comprehensive literature review about dust accumulation on solar PV modules is presented in the first section of this chapter to comprehensively introduce the research on the negative influence of dust accumulation on energy conversion performance of solar PV modules, characteristics of accumulated dust particles (sizes and compositions), effect of environmental parameters including both tilt angles and wind on dust accumulation process and methods for cleaning or preventing dust accumulation. In addition, considering that the dust accumulation process can be regarded as particle deposition process on solar PV module surface, the studies of particle deposition process are also reviewed in this chapter, including the theoretical models for dust deposition velocity calculation and the impacts of various factors (inclination angles, thermophoresis, electrophoresis and surface ribs) on particle deposition velocity. Additionally, because the natural cleaning process for dust accumulation on solar PV modules by wind can be regarded as the process of deposited dust particles re-suspended from solar PV module covers into the ambient air, the studies of particle resuspension process are also reviewed, including experimental results and existing models to describe particle resuspension process. Finally, the flow chart of the research methods used in this thesis is provided.

## 2.2 Introduction Studies on dust accumulation on solar PV modules

### 2.2.1 Decreased influence of accumulated dust on energy output performance of solar PV modules

Hottel and Woertz (1942) firstly investigated the effect of dust accumulation on solar energy systems in the United States. Their tested samples were various solar thermal flat-plate collectors which could absorb received solar radiation and convert solar energy into heat energy. After a three-month experiment, the most important finding was that there was a reduction in the power conversion of the tested solar thermal flat-plate collectors due to dust accumulation with the tilt angle of 30°. In detail, the average reduction was 1% and the largest declination was 4.7%. They also obtained a parameter which was 0.99 for glass material to instruct engineers in designing the solar collectors based on their observed reduction results.

For solar PV modules, Salim, Huraib, and Eugenio (1988) were the early group to investigate the impact of accumulated dust on a solar PV system in Saudi Arabia. Their results revealed that the degradation in energy output performance of tested PV system was 32% in 8 months by comparing an identical and daily cleaned solar PV system with the tilt angle of 24.68$^{o}$. In addition, Wakim (1981) introduced the power generation by solar PV modules in Kuwait and pointed out that the reduction in energy conversion efficiency due to dust accumulation was 17% in 6 days. This result indicated that average daily loss in efficiency was approximately equal to 3% and significantly higher than other known results. Moreover, another interesting finding reported was that the effect of dust accumulation on solar PV modules was lower in autumn and winter than that in spring and summer. Bajpai and Gupta (1988) investigated the performance of silicon solar cells in Nigeria and found that the energy conversion efficiency of dirt solar cell was low compared with other clean samples because of the scattering and absorbing function of dust particles for solar incident light in hot and dusty environment. What's more, Ryan, Vignola, and McDaniels (1989) measured the efficiency of two solar module arrays and pointed out that the average yearly loss in energy conversion efficiency was 1.4% in a 6-year observation due to dust accumulation. Another significant finding of their experiments was the degradation rate in energy conversion efficiency was fluctuant with the change of time. Another study in Saudi Arabia, for maritime-desert-subzone type environment, leading by Said (1990), showed that the efficiency degradation rate of solar PV module samples was 7% per month in one year. This study also compared the loss in efficiency due to dust of solar PV collectors and solar thermal collector and presented that the influence of dust on solar PV systems was more obvious. Additionally, Alamoud (1993) conducted an outdoor experiment in Riyadh, the capital of Saudi Arabia, and proved that the degradation in efficiency was from 5.73% to 19.8% for different types of solar PV modules.

Apart from the investigations above from last century, the degradations of energy efficiency attributed to dust accumulation still remains the research interest in recent two decades and reported by a large number of investigations summarized as follows:

In Dhahran-KSA, the reduction of solar PV power output after six months of outdoor exposure is 50% and the power tracking system could effectively decrease dust accumulation (Adinoyi & Said, 2013). Touati et al. (2013) found that the reduction was 10% after a 100-day outdoor experiment in Qatar and the effect of amorphous solar cells was less than that of crystalline silicon solar cells. Another conclusion reported by the same group was that the 10% loss in efficiency of crystalline solar PV modules caused that the energy requirement of remote areas could not be fully dependent on solar PV modules. Moreover, Boyle, Flinchpaugh, and Hannigan (2013) conducted outdoor experiments in Commerce City for 1.5 years with module glass samples and reported that the reduction of light transmittance was 6% per $g/m^2$ when dust accumulation density was lower than 1.5 g/m$^2$. ElDin et al. (2013) investigated the characteristics of thin film solar PV modules in Alexandria during a 2-month observation and presented that the average loss of power output due to dust particles was 9.86%. Another crucial finding of their work was that short circuit current of solar cells were degraded by17.71%. However, the reduction of open circuit current was less than 2%. M. K. Smith et al. (2013) reported that the loss of power for solar PV arrays was 4% in 17 days in Oregon. Mallineni et al. (2014) investigated some old solar PV Power Plants (4-16 year old) in Arizona and found that the effect of dust accumulation was higher for older solar PV power system.

In conclusion, these studies have only presented that the effect of dust accumulation on energy output performance of solar PV modules was negative and reported various values of reductions in energy output in different areas. In fact, more details, such as the relationship between the loss in energy output power for solar PV modules and dust accumulation density and the effect of dust particle diameters and chemical compositions on the reductions in energy conversion process, need to be studied further.

### 2.2.2 Characteristics of accumulated dust particles on solar PV modules

In general, the characteristics of accumulated dust on solar PV modules vary for different locations. In village areas, there are more nature compositions, such as soil particles blown by wind and excreta from birds. However, in urban areas, pollutants may be dominated the compositions of dust particles. It means that the loss in energy conversion behaviour cannot be equal for the same type of solar PV samples even with the same dust deposition density because of the differences in sizes and compositions of dust accumulation. To investigate the influence of different sizes and compositions on the reduction in energy output power of solar PV modules, many researchers have completed a large amount of work on this problem.

#### 2.2.2.1 Dust particle sizes

Dust particle sizes are generally analysed by optical techniques or scanning electron microscopy (SEM) technology. Biryukov (1996) investigated the particle size distributions on solar collectors and measured the particle deposition rate as a function of particle diameter, as shown in Figure 2.1. In addition, based on measured results, more than 80% of accumulated dust diameters between 5 and 60 μm. Additionally, an interesting work by Al-Hasan (1998), developed the equation to build the relationship between loss due to accumulated dust and dust accumulation size and density. In this model, dust particles were assumed to be spherical and developed equation could precisely analyse experimental results. Ju and Fu (2011) also analysed the influence of particle sizes on the change of light transmittance for glass covers.

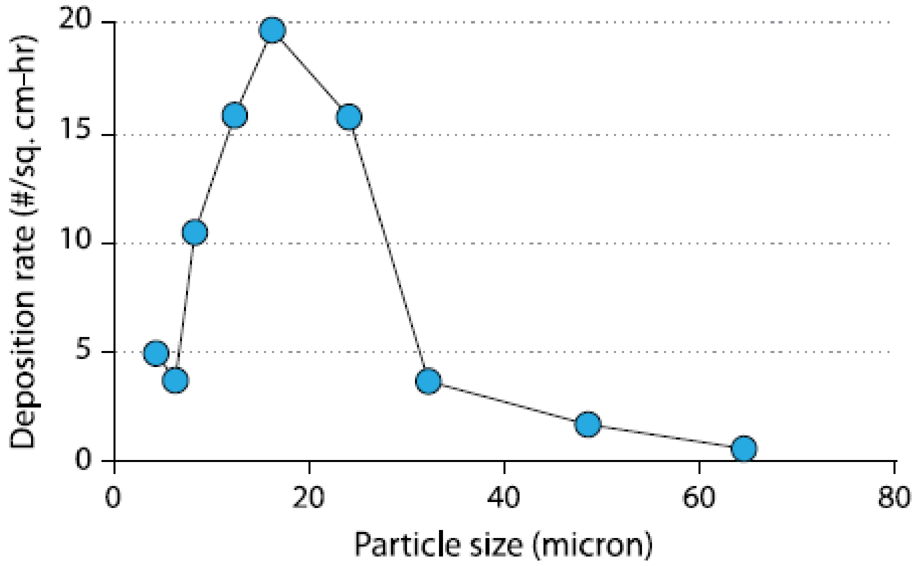



Figure 2.1 Deposition rates on solar mirror according to particle sizes (Biryukov, 1996).

#### 2.2.2.2 Dust compositions

As we know, the compositions of dust particles can present environmental properties of installed areas. With the help of X-ray diffraction (XRD) method, Elminir et al. (2006) comprehensively investigated the chemical compositions of dust accumulation in Egypt. Based on their results from Figure 2.2, the main elements of dust accumulation are silicon and calcium. Silicon and calcium were primarily from desert sand and mineral respectively. Thus, the main compositions for dust particles were quartz ($SiO_2$) and calcium carbonate ($CaCO_3$) and the minor components were $Al_2O_3$, MgO and $Fe_2O_3$. They also pointed out that the presence of coarse Si showed the emission from the desert areas and the resuspension of dust particles due to the activity of human. Besides, the reason for Ca was the emanation from some cement factories near the tested region and some building activities. The significance of dust particles from traffic was indicated by the presence of small concentrations of three common elements, Al, Mg and Fe. Z. A. Darwish, H. A. Kazem, K. Sopian, M. Al-Goul, and H. Alawadhi (2015a) investigated the compositions of dust particles from four different areas in United Arab Emirates during the whole year of 2013 and showed similar results as Elminir et al. (2006).

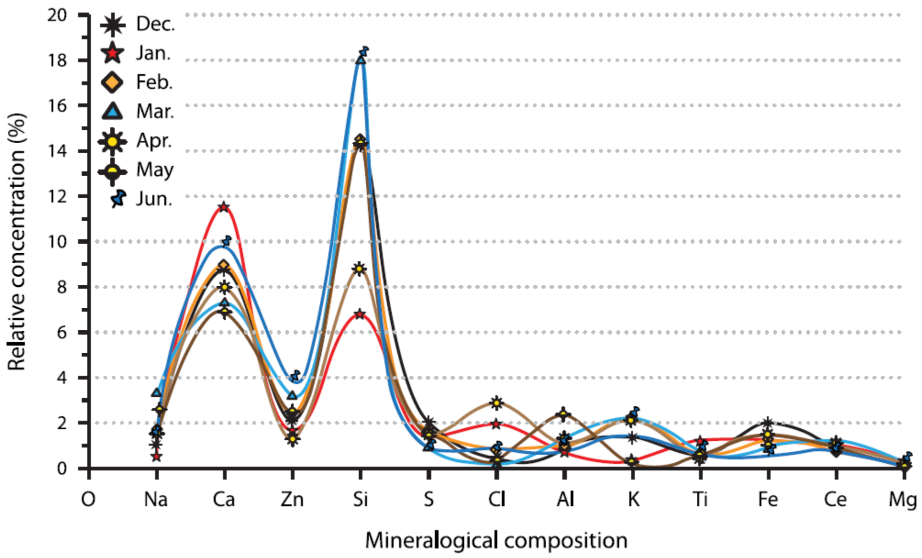



Figure 2.2 X-ray diffraction analysis of the dust particles for different months (Elminir et al., 2006).

In addition, the compositions of accumulated dust particles are reported by other research groups. Their results show that the compositions of dust particles are various in different times, even in one same region. So, the best way for engineers to decide the compositions of dust particles is conducting composition analysing experiments and theoretical models are difficult to describe this issue.

Apart from the compositions of accumulated dust, El-Shobokshy and Hussein

(1993) fully investigated the influence of different compositions for dust particles on solar cells. They used various artificial dust particles to test, such as cement of 10 μm, limestone of 50, 60 and 80 μm and carbon of 5 μm. Their results presented that fine particles considerably decrease the energy conversion efficiency of solar cells more than coarser particles. Carbon particles, due to the small particle size, has the maximum negative effect for solar cells than other compositions.

Although characteristics of accumulated particles have been fully studied, including particle sizes and compositions, the equation to quantitatively evaluate the relationship between deposition density and energy loss is not proposed and need to be further examined.

### 2.2.3 Influence of environmental parameters on dust accumulation on solar PV modules

In addition to the physical and chemical characteristics of deposited dust particles, there is no denying that environmental factors can enormously affect dust accumulation process on solar PV modules. In this section, the studies of two critical environmental parameters, wind from the atmospheric air and inclination angles of operational solar PV modules, are summarized.

#### 2.2.3.1 Wind velocity and orientations

To systematically study the effect of wind, wind tunnel simulations and field experiments were carried out respectively in the Negev Desert (Goossens et al., 1993;

K. Smith & Goossens, 1995). Their experimental setup is presented in Figure 2.3. They reported that wind directions which provided by west and east mirrors can considerably affect the deposition density and size distribution of accumulated dust. For north and north-west directions, velocity for dust deposition was largest at noon, on the other hand, deposition velocity was largest for west and south-west wind directions in the afternoon. In addition to wind orientations, the deposition density was large for high wind velocity. However, the impact of wind velocities which is higher than 2 m/s is small. In addition, one paper reported higher wind velocity can result in serious dust accumulation on solar cells (Goossens & Van Kerschaever, 1999).

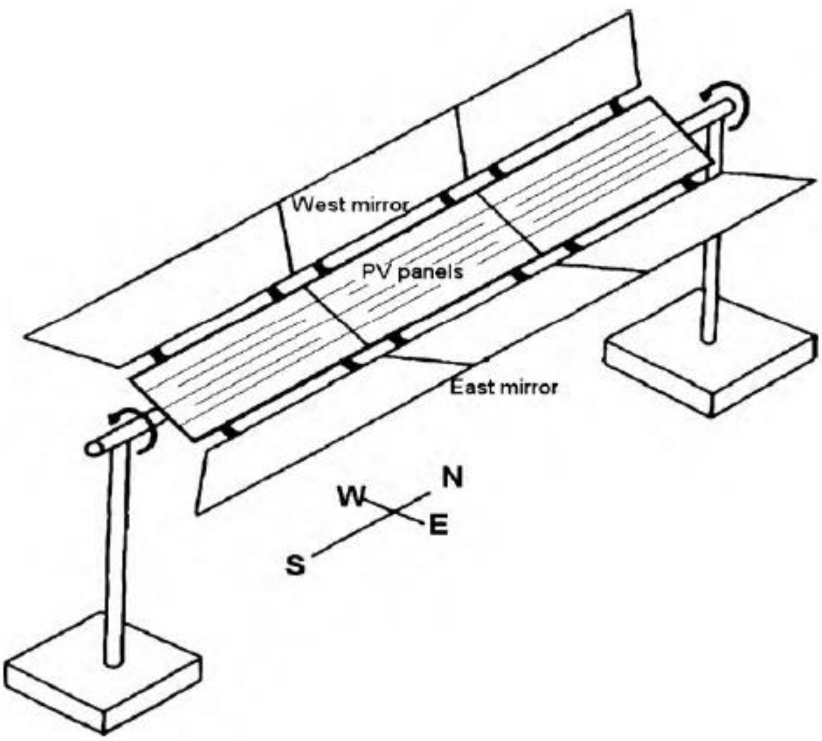



Figure 2.3 Experimental setup for investigating dust deposition under various wind conditions (Goossens et al., 1993).

#### 2.2.3.2 Tilt angles

In addition to wind velocity and orientation, installation tilt angle of solar PV modules is another significant parameter which can greatly affect dust accumulation density for solar PV modules. Elminir et al. (2006) conducted experiments to investigate the effect of tilt angles. In their experiments, they used the loss in light transmittance for glass samples to examine dust accumulation because dust accumulation mainly happened on glass covers. Besides, seven tilt angles from 0 to 90 degree with 15 incidents and eight different orientations were tested. Figure 2.4 presents the loss in light transmittance due to the soiling effect. Their results obviously showed that the reduction of light transmittance owing to dust accumulation was decreased with the increase of tilt angles. They also explained the results of different orientations and pointed out that the northeast winds had the largest effect because the cement particles mainly generated from the factories of this direction. An equation for evaluating the relationship between dust deposition density and the change of light transmittance is proposed in their work, but only applied for their results.

| Tilt angle | Orientation of glass samples | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | N | NE | E | SE | S | SW | W | NW |
| 15° | 19.71 | 20.89 | 20.52 | 20.17 | 20.28 | 20.17 | 20.02 | 19.69 |
| 30° | 18.72 | 18.86 | 18.50 | 19.61 | 18.87 | 17.66 | 17.72 | 17.85 |
| 45° | 16.34 | 18.31 | 15.32 | 15.82 | 15.72 | 15.86 | 14.27 | 16.02 |
| 60° | 15.13 | 14.71 | 13.42 | 12.71 | 12.81 | 13.94 | 12.85 | 13.41 |
| 75° | 9.67 | 13.97 | 10.24 | 9.73 | 9.25 | 8.82 | 12.37 | 12.51 |
| 90° | 8.07 | 6.84 | 5.85 | 4.94 | 6.11 | 6.23 | 5.81 | 6.73 |

Figure 2.4 Reductions in transmittance for different directions and tilt angles(Elminir et al., 2006).

Additionally, Mejia and Kleissl (2013) investigated the losses of solar photovoltaic systems in California because of soiling and observed that tested sites with small tilt angles had larger value in loss. Additionally, one study with 9 different tilt angles from 0° to 40° indicated that the loss of solar PV modules was 2.02% for horizontal position, 1.05% for 23° tilt angle and 0.96% for 33° tilt angle respectively from January to March (Cano, John, Tatapudi, & TamizhMani, 2014). The similar conclusions of the influence have also been reported by other researchers (Bashir, Ali, Khalil, Ali, & Siddiqui, 2014; Chamaria, Dube, & Mittal, 2014; Gandhi, Gupta, & Shyam, 2014; Mallineni et al., 2014; Negash & Tadiwose, 2015; Qasem, Betts, Müllejans, AlBusairi, & Gottschalg, 2014). Therefore, it can be found that large tilt angles could greatly decrease the dust accumulation density for solar PV modules and thus maintain its high energy conversion performance.

Even though environmental parameters of tilt angles and wind have been studied in detail, the influence of operating solar PV modules characteristics, including both temperature differences and generated current due to energy conversion process, on dust accumulation needs to be further investigated.

### 2.2.4 Methods for cleaning or preventing dust accumulation on solar PV modules

Considering the negative effect of dust accumulation on the energy conversion performance of solar PV modules as introduced in previous sections, studies of approaches for removing or stopping dust accumulation thus have received lots of attentions. Hence, in this section, the main approaches to deal with dust accumulation are reviewed so as to indicate the issues which need to be investigated in future.

#### 2.2.4.1 Removing approaches

When it comes to cleaning solar PV module surface with dust accumulation, water is the first one to be selected because it is an effective medium to remove dust particles. For many regions, nature can provide sufficient water by different types of phenomena, such as rain or snow. Roth and Pettit (1980) observed that rain and snow increased 12% reflectance during a 480 days exposure experiment.

However, the water supply in many areas from nature is not enough for cleaning dirt surface, especially for desert areas where solar PV plants can be large scale due to sufficient room and abundant sunlight. At this time, the assistance from human need to be employed. In addition to normal water, many researchers have verified that the cleaning performance of chemical solutions is better and the best cleaning time for cleaning was morning to reduce the damage to glass covers (Sheratte, 1980). Effective chemical solutions should have advantages of low cost, ability of decreasing surface tension and safe for human beings.

Except for cleaning methods based on fluid, another simple way is mechanically removing method, such as wiping the covers with different mediums. However, this method can destroy the structure of solar PV module surface and therefore lead to negative impact on light transmittance of glass covers. Another method is air flow which means that deposited dust particles are re-suspended by forced air across glass covers. Schumacher, Hansen, and Nevenzel (1979) compared the performance of different techniques based on air flow technology on cleaning accumulated dust. They reported that vortex nozzle technique had good performance on removing dust particles. The requirement of the application of vortex nozzle technology was that air flow should be close to targeted surface. In addition, air with ultrasonic energy assist in removing had the best performance in cleaning experiments.

#### 2.2.4.2 Preventing approaches

There are several preventing approaches for dust accumulation on solar PV modules. The first one is surface modifications. It means that modified glass covers due to some chemical compounds of solar PV modules can reduce the whole dust accumulation density. Cuddihy (1980) proposed several instructions for the designed surface of low soiling. They includes smooth, hard, low surface energy, hydrophobic character and chemically clean. He, Zhou, and Li (2011) summarized two common chemical modification methods for solar cells. The first technique is hydrophilicity film and the most popular material for this technique is $TiO_2$. $TiO_2$ film has two characteristics which are hydrophilicity and photocatalytic activity respectively. There are two stages in the cleaning dust particle process of this film. The first one is that this film can effectively split the organic compositions of dust under the solar light. Then, the left compositions can be easily washed away by the rainwater. Another technique is super hydrophobic film. Because the contact angle of the surface with super hydrophobic film is higher than $150^o$, the water droplets can form roll off position and quickly wash dust particles with this statues. Nevertheless, the problem for this two chemical modification methods is that these two methods cannot be used in desert areas because of the shortage of rainwater resource.

In addition, active prevention approaches are innovative methods for cleaning dust accumulation with less labour. MK Mazumder et al. (2007) developed one self-cleaning dust shields with help of electrodynamic screens (EDS), as presented in Figure 2.5. This EDS system contained one high voltage power supply and deposited transparent conductive electrodes with 50 μm high and 100 μm wide. Particles on this shields could be charged and removed by the vertical component of the generated electric field on the surface. Efficiency of this technique was high and nearly 95% could be cleaned.

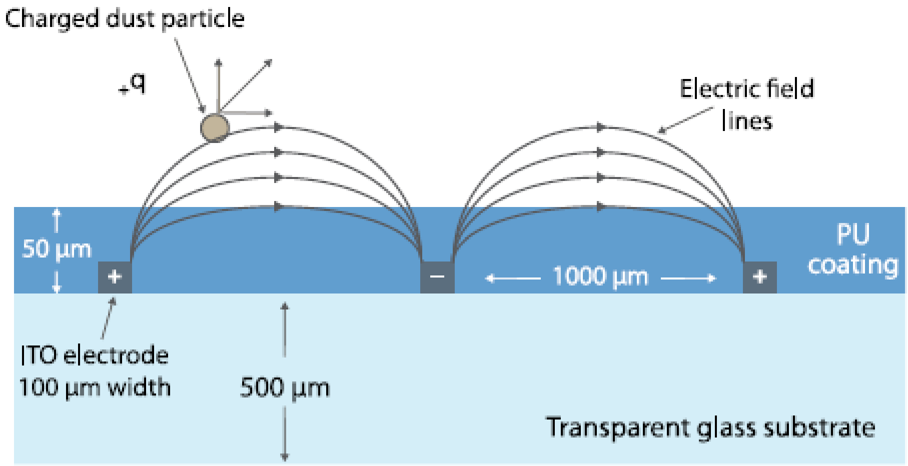



Figure 2.5 Cross section of electrodynamic screen (EDS) (MK Mazumder et al., 2007).

However, few reports have focused on another significant issue for cleaning PV modules with dust particles, the cleaning frequency, especially for desert areas and the details of wind cleaning process is limited. So, the method for calculating cleaning frequency and describing the wind cleaning process for dust accumulation needs to be developed.

## 2.3 Studies on particle deposition process

As stated in Chapter 1, particle deposition process can be observed in different environments and has negative effect on deposited surfaces. Thus, modelling the velocity of particle deposition is significant for researchers to evaluate the adverse influence due to particle deposition and design novel methods to deal with this problem. Then, the main part of this section is reviewing the model of particle deposition velocity and introducing the impact of different parameters on deposition velocity.

### 2.3.1 Modified three layer model for particle deposition velocity

As introduced before, the three-layer model, firstly proposed by Lai and Nazaroff (2000), has been proved that this model can effectively and accurately estimate the rate of particle deposition in turbulent flow. The original form has been shown in Eq. (1.1). However, in the original equation, one significant mechanism for particle deposition process, turbophoresis, has not been considered. Therefore, the modified form of this three-layer model, developed by Zhao and Wu (2006a), can be expressed as follows:

$$J = -\left(\varepsilon_p + D\right)\frac{\partial C}{\partial y} - iv_s C + V_t C, \tag{2.1}$$

where $V_t$ means the deposition velocity of due to turbophoresis.

Caporaloni, Tampieri, Trombetti, and Vittori (1975) firstly studied the turbophoresis phenomenon in particle movements and expressed the deposition velocity due to turbophoresis as:

$$V_t = -\tau_p \frac{d\overline{v_{py}'^2}}{dy} \tag{2.2}$$

where $\tau_p$ means the particle relaxation time and can be expressed as:

$$\tau_p = \frac{C_c \rho_p d_p^2}{18\mu} \tag{2.3}$$

where $\mu$ is the air molecular dynamic viscosity, $\rho_p$ is the particle density, $d_p$ is the particle diameter and $C_c$ is the Cunningham coefficient (Zhao & Wu, 2006a).

Then the three layer model can be expressed as:

$$J_{(u^*,d_p)} = -\left(\frac{\tau_L}{\tau_p+\tau_L}\upsilon_t + \frac{k_B T C_c}{3\pi\mu d_p}\right)\frac{\partial C}{\partial y} - iC_c\left(\frac{4}{3}\cdot\frac{g\cdot d_p}{C_D}\frac{\left(\rho_p-\rho\right)}{\rho}\right)^{1/2} C - \tau_p \frac{d\left[\frac{\tau_L}{\tau_p+\tau_L}\overline{v_y'^2}\right]}{dy} C \quad (2.4)$$

In general, this modified three-layer particle deposition model can accurately estimate particle deposition velocity in fully developed and smooth turbulent duct flow, as shown in Figure 2.6. However, due to the difficulty in calculate the eddy diffusivity, estimating particle deposition velocity by modified three-layer model is challenge.

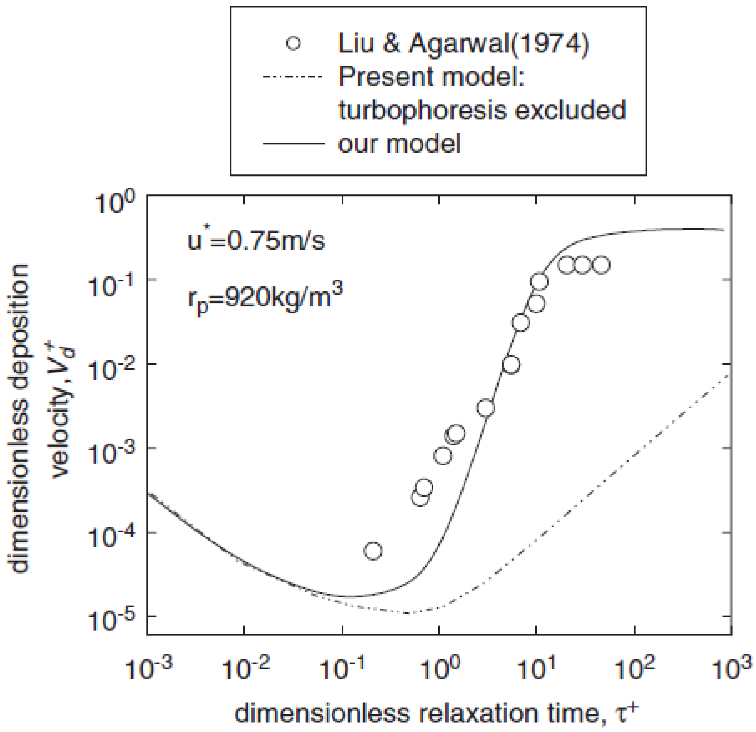



Figure 2.6 Comparison of predicted results by original and modified three-layer model with experimental data (Zhao & Wu, 2006a).

### 2.3.2 Influencing factors for particle deposition velocity

Recently, due to a great many comprehensive studies on particle deposition behaviour in turbulent flow, significant influencing parameters for deposition process are inclined angles of deposited surface, thermophoresis due to the temperature differences between airflow and deposited surfaces, electrophoresis generated from deposition areas and surface ribs. Hence, the effect of these factors on particle deposition velocity is summarized as follows:

### 2.3.2.1 Influence of tilt angles

Tilt angles can dramatically influence the particle deposition velocity. Based on the modified three-layer model above, You, Zhao, and Chen (2012) developed empirical equations for particle deposition velocity in turbulent flow.

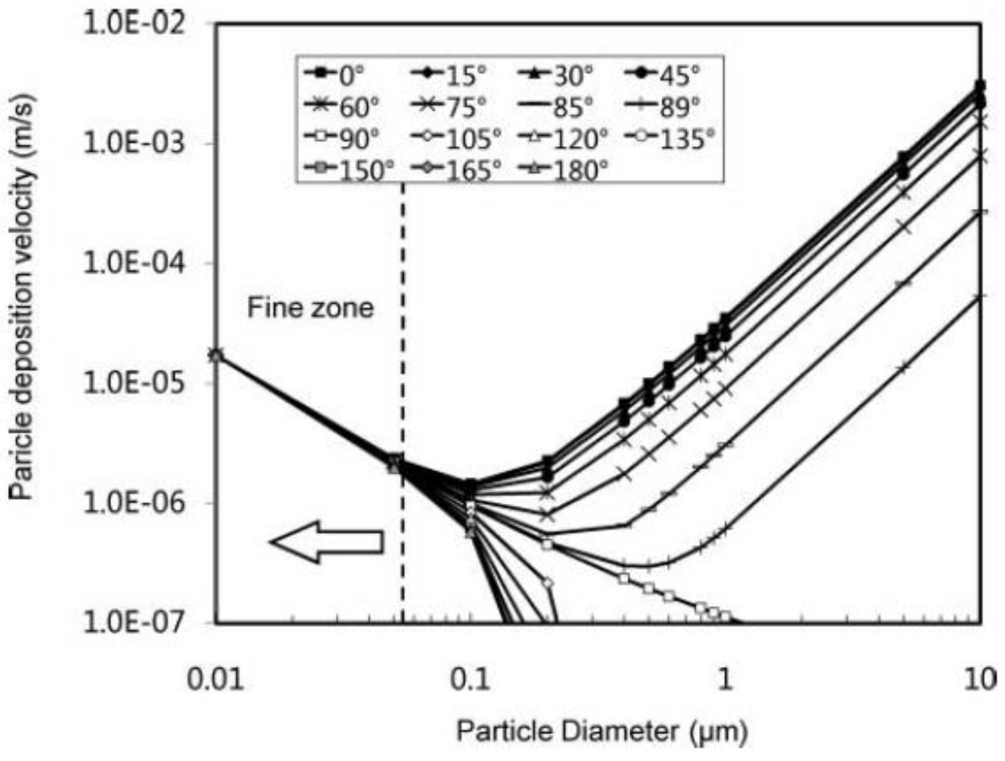



Figure 2.7 Particle deposition velocities for fine zone particles with different inclination angles (u∗ = 1 cm/s) (You et al., 2012).

As presented in Figure 2.7, tilt angles significantly affect particle deposition velocity of particles whose diameters are larger than 0.5 μm because gravity plays a significant role in particle deposition process for large particles. Thus, it can be found that particle deposition velocity decreases with the increase of inclination angles. However, the experimental studies to verify the effect of tilt angles are seldom. Hence, the experimental work is strongly recommended in order to fully clarify the relationship between inclination angles and particle deposition velocity.

### 2.3.2.2 Influence of thermophoresis

Thermophoresis means that particles tends to move from areas with higher temperature towards regions with lower temperature when subjected to temperature gradient. The thermophoretic force can be measured according to the balance of drag forces with thermophoretic force. So the commonly used expression for thermophoretic force is given by (Talbot, Cheng, Schefer, & Willis, 1980):

$$F_{th} = -\frac{3\pi\mu^2 d_p H}{\rho_a T}\frac{dT}{dy} \tag{2.5}$$

where *dT/dy* is the *y*-component of the temperature gradient and *H* is the thermophoretic force coefficient, expressed as:

$$H = \left(\frac{2.34}{1+3.42Kn}\right)\left(\frac{k_a / k_p + 2.18Kn}{1+2k_a / k_p + 4.36Kn}\right) \tag{2.6}$$

Here, $k_a$ and $k_p$ are the thermal conductivities of the air and the particle material, respectively. The thermophoretic velocity, obtained when the thermophoretic force is balanced by drag force is:

$$v_{th} = \frac{-C_c \nu H}{T} \frac{dT}{dy} \tag{2.7}$$

The thermophoretic velocity in a given temperature gradient is at a maximum and nearly independent of particle size for particles smaller than 1 μm. For larger particles, the thermophoretic velocity decreases with increasing particle size, provided that $k_a/k_p$ < ~0.2. Lower values of $k_a$ / $k_p$ also lead to lower thermophoretic velocities for larger particles. Figure 2.8 shows the numerically investigated thermophoretic deposition of particles in turbulent air duct flows by modified v2-f turbulence model. When the wall is heated or cooled, the cross-stream temperature gradients generate thermophoretic force on the particles which can affect the deposition rate significantly. For a cooled wall, when the wall temperature is below the mean gas temperature, thermophoretic force increases the deposition rate. As presented in Figure 2.8, enhancing temperature differences increases the particle deposition velocity. This figure also shows that the experimental data are in good agreement with the calculations. It is obvious that for small particles the small temperature differences create significant changes on the rate of particle deposition.

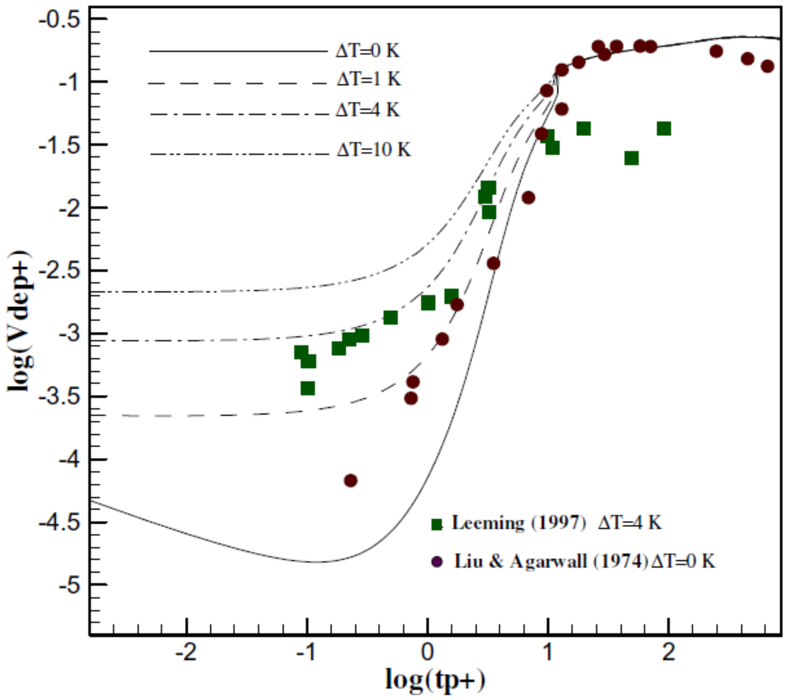



Figure 2.8 Effect of thermophoresis on particle deposition velocity in turbulent duct flow.

### 2.3.2.3 Influence of electrophoresis

Li & Ahmadi present an equation that predicts the electrostatic force on a charged particle near a conducting surface as:

$$F_e = qE - \frac{q^2}{16\pi\varepsilon_o y^2} + \frac{qEd_p^3}{16y^3} - \frac{3\pi\varepsilon_o d_p^6 E}{128y^4} \qquad (2.8)$$

where $\varepsilon_o$ is the permittivity of air. The terms on the right side of equation present the Coulomb force, image force, dielectric force and dipole-dipole force respectively. Li & Ahmadi's analysis suggested that the dielectric force and the dipole-dipole force are negligible and that the Coulomb force dominates when an electric field is present. Because of the use of electrically conducting materials, significant electric fields are not expected in HVAC ducts. In the absence of an electric field, the only component of the electrostatic force that can influence particle motion is the image force. The image force is always directed towards a wall and is only appreciable extremely close to a wall. It only occurs near a conducting surface. Charges accumulated on electrically insulating materials may give rise to electric fields and influence the motion and deposition of charged particles. Electrophoretic deposition of particles in turbulent air duct flows was conducted by modified v2-f turbulence model, as shown in Figure 2.9.

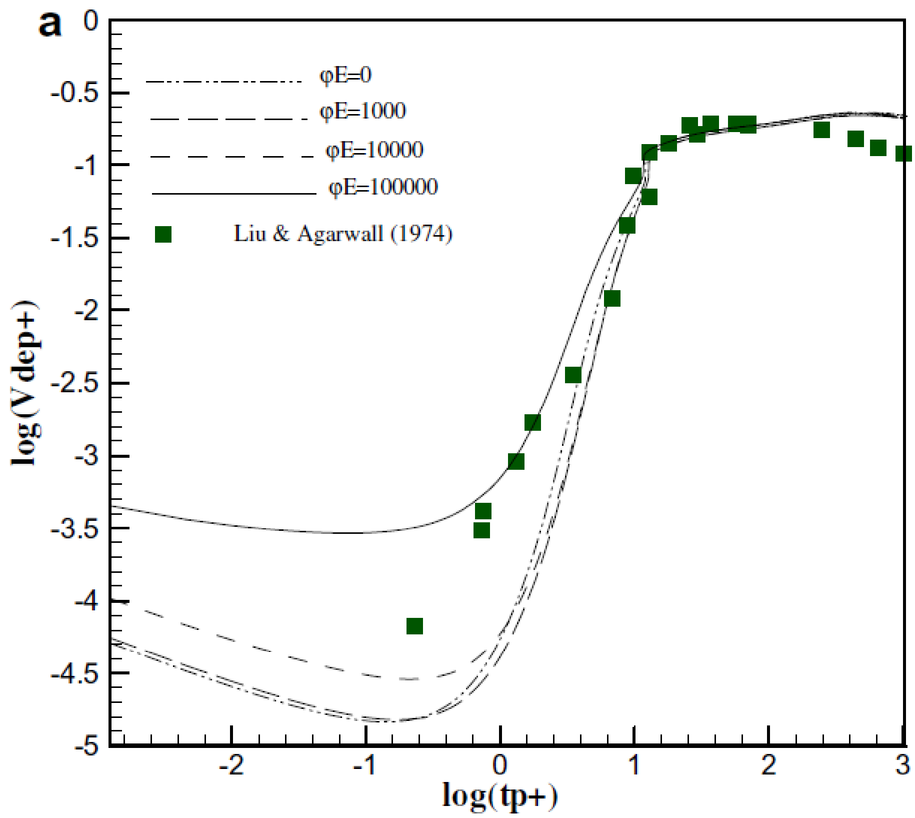



Figure 2.9 Effect of electrophoresis on particle deposition velocity in turbulent duct flow.

Figure 2.9 shows that the electric field can greatly increases the deposition velocity, especially significant for small size particles. This strong effect is caused by the turbulent migration of particles into the wall boundary layer which is enhanced as a result of the electrostatic force. The electrostatic force due to electric field is dominant in $t_p$< 1. It is even more important than the Brownian diffusion and turbulent dispersion near the wall. Therefore, resistance for near-wall zone is lowered when the particle charge is increased and the deposition rate will increase accordingly.

#### 2.3.2.4 Influence of surface ribs

In a great many systems, it is important to increase the velocity of particle deposition because these systems are designed to removal particles in the ambient air. Due to the increasing effect of surface ribs on heat transfer process, the influence of surface ribs on particle deposition in turbulent flow are numerically studied by CFD simulation (H. Lu & Lu, 2015a, 2015b, 2015c, 2016). Firstly, it is obvious that surface ribs can drastically increase particle deposition velocity. In detail, the deposition enhancement due to surface ribs for small particles ($\tau_p^+ < 1$) is much higher than that for large particles ($\tau_p^+ > 1$). When $\tau_p^+ < 1$, the dimensionless particle deposition velocity can be increased by almost four orders of magnitude for the ribbed surface, while it is only enhanced by about two orders of magnitude when $\tau_p^+ > 1$. In addition, the impact of different surface rib shapes, rib spacings and rib heights are also analysed. For instance, comparing with triangular and circular ribs, the square ribs have the most enhancement on particle deposition velocity for small particle, as shown in Figure 2.10 and 2.11.

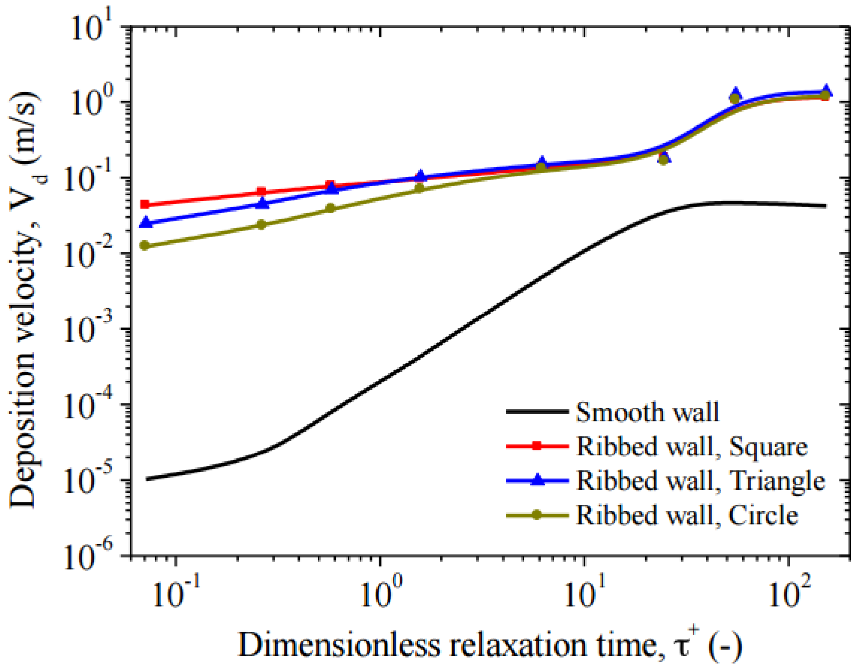
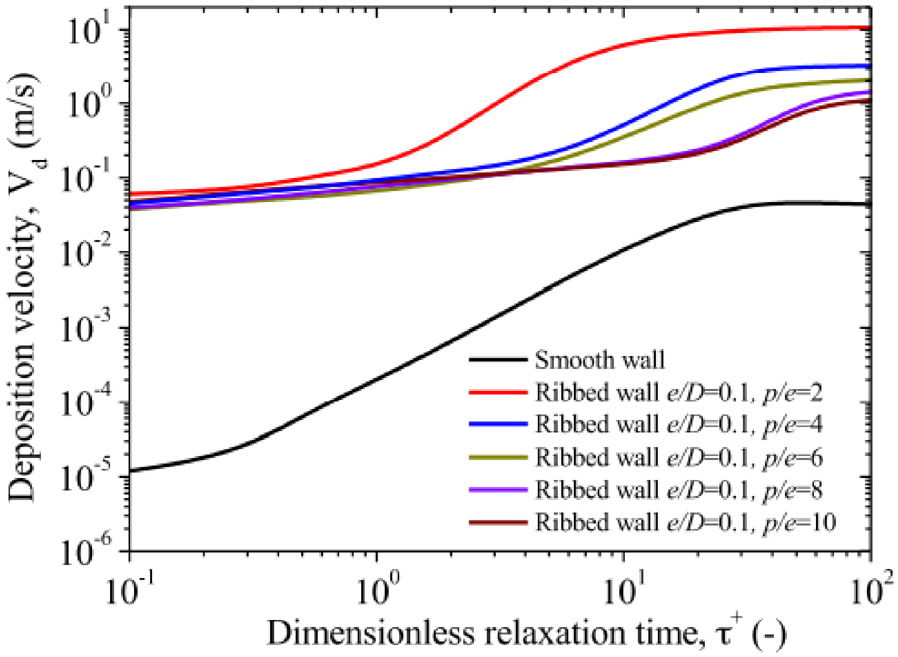
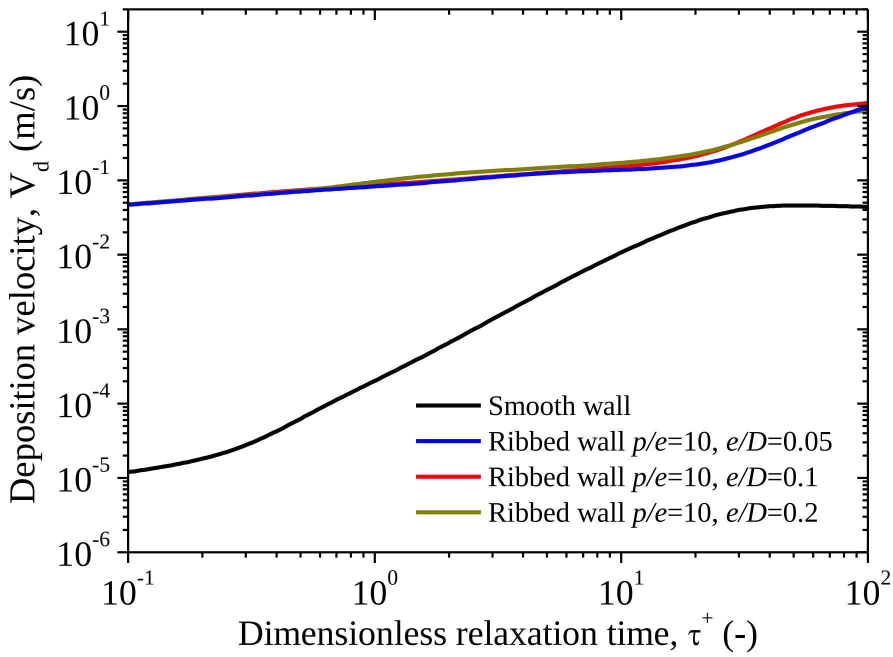



Figure 2.10 Particle deposition velocity for ribbed-wall ducts with different rib shapes (H. Lu & Lu, 2015c).

Except for the interception by the windward rib surfaces and the increase of deposition area, the entrainment of turbulent eddies induced by the surface ribs are the main mechanism for small size particles. The turbulent structures for ribbed ducts are quite different to those for the smooth duct. In the latter case, the flow is along the streamwise direction and the T.K.E value near the wall is very small. For ribbed ducts, small particles are easy to be captured by the vortices in the rib cavity and then entrained to be deposited on the rib surfaces or walls. The T.K.E. near the surface ribs is higher than that for smooth duct flow. Therefore, the arrangement of surface ribs is an efficient and effective way to enhance particle deposition, especially for small size particles.




(a) Different rib spacings




(b) Different rib heights

Figure 2.11 Particle deposition velocity in ribbed duct flow with different rib spacings and heights.

## 2.4 Studies on particle resuspension process

Particle resuspension means that deposited particles on surfaces can be re-suspended or removed from the deposited surface into the ambient air and this phenomenon can occur in various environments. Firstly, resuspension of airborne particles in indoor or outdoor environments, such as heating ventilation air conditioning refrigeration (HVACR) systems, indoor environment due to movements of occupants or industrial applications, has adverse effect on the health of human beings. Secondly, particle resuspension can take place in different industrial fields, such as the radioactive particles from the nuclear industry or the destructive particles from the fire in the energy field and spores from bacillus species in food industry (Kissane, Zhang, & Reeks, 2012; Mercier-Bonin, Dehouche, Morchain, & Schmitz, 2011; Ouf et al., 2013). Last but not least, particle resuspension can happen in filtration systems to avoid membrane fouling problems in applications in pharmaceutical, food, waste water and desalination industries.

So, considering the significant influence of particle resuspension on different fields, researchers have comprehensively investigated the particle resuspension, including experimental studies on particle resuspension process, model to calculate particle resuspension velocity or resuspension fraction, mechanisms for particle resuspension in monolayer or multilayer surface. Details of these studies are introduced as follows:

### 2.4.1 Experimental studies on particle resuspension from monolayer deposits

Firstly, because the drive forces for particle resuspension process are from fluid, the influence of particle-fluid interactions have been experimentally investigated for many years. Light scatting methods are common to measure the quantity of particles on experimental surface at different times under sufficient fluid and the rate of resuspension can be accurately calculated by measured numbers of particles. From all existing studies on this field in different conditions, it can be obviously observed that the amount of particles increase with the increase of fluid velocity (Gradoń, 2009). Consequently, a threshold velocity has been generally defined as the required velocity for particle removal in particle resuspension process (Phares, Smedley, & Flagan, 2000).

In addition to particle-fluid interactions, particle-surface interactions can dramatically affect particle resuspension process. In fact, particle can be removed from deposited surface when the adhesion forces between particles and deposited surface are lower than the drive forces from fluid. One significant technology, which is named atomic force microscopy (AFM) technique, has been extensively used in experimental work to investigate the particle-surface interactions, especially measuring adhesion forces between them. A large number of studies have verified that particle-surface interactions are strongly depended on the properties of particles and surface, such as the particle size, particle compositions and surface compositions.

Besides, the enormous influence of surface morphology on particle resuspension process due to different reasons have been widely reported. For example, two different kinds of particle resuspension (PMMA and glass) from stainless steel surface with various roughness has been measured in an airflow channel (Y. Jiang, Matsusaka, Masuda, & Qian, 2008). Results of this particle resuspension experiment are presented in Figure 2.12. The most obvious finding is that the fraction of re-suspended particles increases when surface roughness increases.

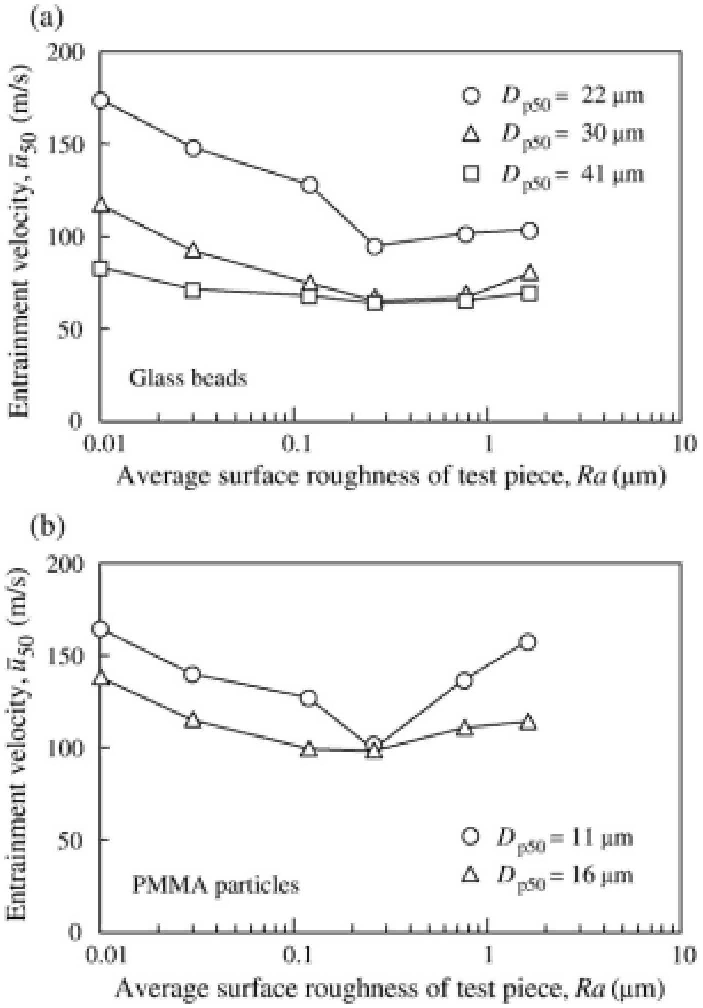



Figure 2.12 Effect of the surface roughness on particle resuspension process ((a) glassbeads, (b) PMMA particles) (Y. Jiang et al., 2008).

### 2.4.2 Mechanisms for particle resuspension from monolayer deposits

Actually, particle resuspension is the result of complicated interactions between disruptive forces and cohesive forces. These two different kinds of force have opposite influence on particle resuspension process. The disruptive forces can removal particles from deposited surface and the cohesive forces can maintain particles on deposited surface. Disruptive forces resulting from hydrodynamical forces and cohesive forces are mainly from the interactions between deposited particles and surface.

Firstly, deposited particles on a specific surface and exposed to a flow are commonly subjected to two main hydrodynamic forces, drag and lift forces, as illustrated in Figure 2.13. Drag forces are traditionally expressed by a functional form:

$$F_{drag} = \frac{1}{2} C_D U_r^2 A_p \rho_f \tag{2.9}$$

where $U_r$ is the slip velocity, $A_p$ is the particle cross-sectional area exposed to the flow, $\rho_f$ is the density of fluid and $C_D$ is the drag coefficient.

In addition, for lift force, the general expression for a spherical particle with small Reynold's number can be written as:

$$F_{lift} = 9.22(\tau_f \mu_f R_{part}^2)(\frac{\tau_f R_{part}^2}{\upsilon_f}) \tag{2.10}$$

where $\tau_f$ is the shear rate.

In addition to two types of hydrodynamic forces presenting particle fluid interactions, particle-surface interactions are significant in particle resuspension process.

Firstly, JKR theory is one of contact theories and therefore common used in particle-surface interactions calculation process. The basic assumption of JKR theory is that particles and surfaces are fully elastically deformed and thus the adhesion is within the contact area. So the adhesion force based on JKR theory is written as:

$$F_{JKR} = 3\pi \Delta r R_{part} \tag{2.11}$$

Another theory to describe particle surface interactions are called DMT theory. This theory is similar to JKR theory but considers noncontact force such as van der Waals force. Hence, adhesion force based on DMT theory is obviously larger than that of JKR model and can be presented as:

$$F_{DMT} = 4\pi \Delta r R_{part} \tag{2.12}$$

Therefore, based on the equations of hydrodynamic forces and adhesion forces, the minimum velocity for particle resuspension can be calculated.

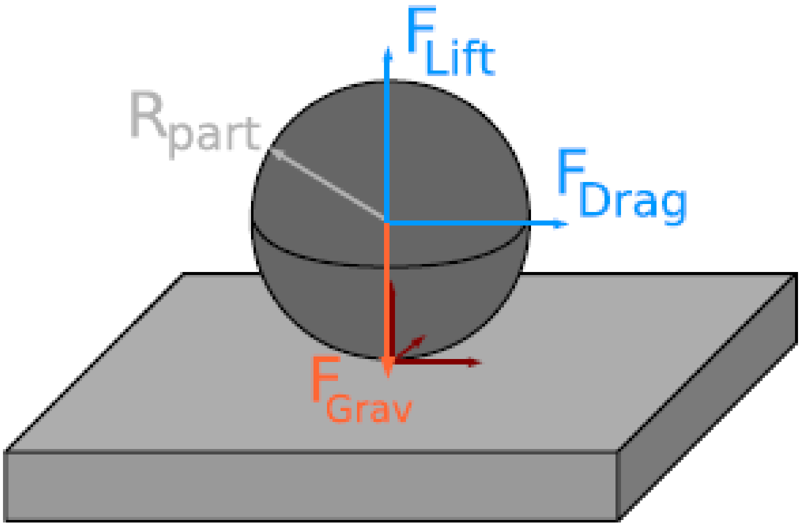



Figure 2.13 Sketch of different hydrodynamical forces for particle resuspension.

### 2.4.3 Existing models for particle resuspension from monolayer deposits

Recently, a great many models to evaluate particle resuspension process have been developed. The first category is empirical models. In addition, a novel empirical equation was developed by the dimensional analysis and choosing significant parameters according to the mechanisms of particle resuspension process. This empirical equation can be written as (Henry & Minier, 2014):

$$k_r = c_0 \frac{u_r}{d_p} \left(\frac{\rho_p}{\rho_f}\right)^{c_1} \left(\frac{u_r t}{d_p}\right)^{c_2} \left(\frac{d_{asp}}{d_p}\right)^{c_3} \left(\frac{A_{Ham}}{d_p^2 (u_r)^2 \rho_f}\right)^{c_4} \tag{2.13}$$

Consequently, the obvious advantage of empirical models for particle resuspension process is that these equations can rapidly obtain the calculated results. Nevertheless, these empirical equations are only validated in the founders' experiments, not suitable for other conditions. Thus the applications of empirical models are limited.

The second category of particle resuspension models is based on static force-balance approaches. This approach contains two balances. The first one is force balance of adhesion force, hydrodynamic forces and gravity force. The second one is the moment balance of forces above. These balances can be illustrated as follows:

$$F_{adh} + F_{hydro} + F_{grav} = 0 \tag{2.14}$$

$$M_O(F_{adh}) + M_O(F_{hydro}) + M_O(F_{grav}) = 0 \tag{2.15}$$

## 2.5 Research method

As discussed in previous sections, operating solar PV modules can result in temperature differences between solar PV module and its ambient environment, and generate current which will cause electric field when converting received solar energy into utilized electrical energy. The influence of these two generated phenomena on dust accumulation have never been reported and examined. In fact, for particle deposition process, the thermophoresis due to temperature difference and electrophoresis due to electric field can affect the deposition velocity significantly. Consequently, the study of the effect of temperature difference and generated current is presented in Chapter 3 and Chapter 4 in details respectively. Based on dust particle deposition experiments in the designed chamber, the deposition densities and transmittance ratios for glass samples and output power for actual monocrystalline silicon PV module samples are measured to reveal the influence of temperature differences and generated current due to energy conversion process on dust accumulation.

In addition, considering the limited research of cleaning process, including wind cleaning process and cleaning frequency, the method to calculate the wind cleaning process based on particle resuspension model is presented in Chapter 5. Wind cleaning process for deposited dust particles means that deposited dust particles can be re-suspended by air flow. Similarly, the method to evaluate THE cleaning frequency based on particle deposition velocity model is developed and more details are demonstrated in Chapter 6.

A flow chart for the research method in this dissertation is shown in Figure 2.14.

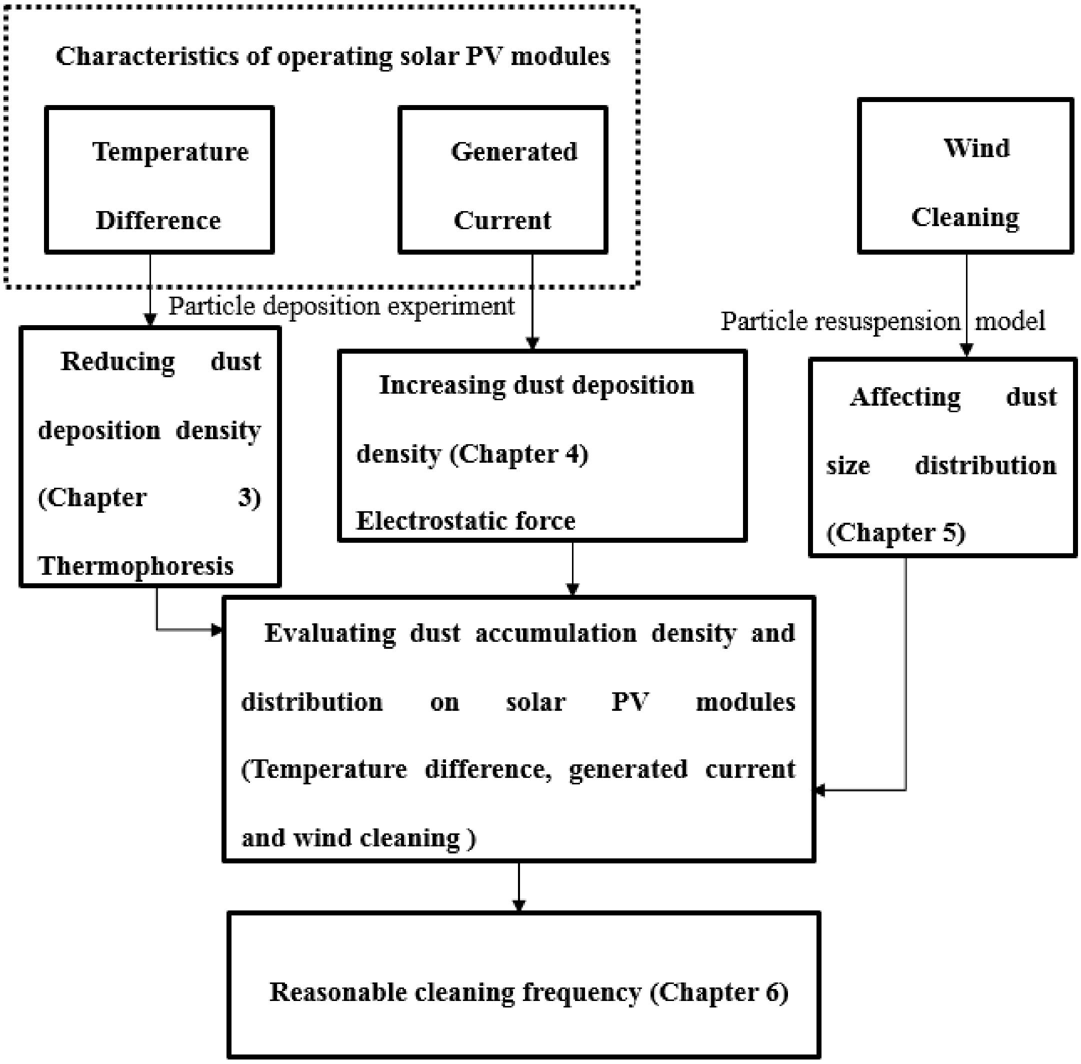



Figure 2.14 A flow chart of the research method for this thesis.

# CHAPTER 3

# INVESTIGATING THE INFLUENCE OF TEMPERATURE DIFFERENCES ON SURFACE DUST ACCUMULATION PROCESS FOR SOLAR PV MODULES

## 3.1 Introduction

As introduced in Chapter 1 and Chapter 2, the previous studies seldom investigated the influence of operational solar PV modules on dust accumulation process. However, the temperature differences between solar PV module surface under sufficient solar radiation and local ambient air are obvious which can result in a temperature gradient near glass covers and thus a force called thermophoresis force. Thermophoresis force can be applied to submicron particles moving toward cold surface or blowing away from a hot surface at a given temperature gradient. Therefore, the rising temperature difference may reduce the dust accumulation rate and increase the power output of solar PV modules due to the direction of thermophoresis force. Thus, this influence should be examined by indoor particle deposition experiments. So, the primary work for this chapter is listed as follows:

1) The influence of temperature differences on dust accumulation process for normal glass surface is examined. The effect of tilt angle on dust deposition is

qualitatively studied, and the deposition velocity because of temperature differences is analysed based on the comparison of calculation and experimental results.

2) Measuring results of accumulated dust particle density and the energy output power of tested solar PV module samples are presented to illustrate the influence of temperature differences on dust accumulation process. The short circuit current and the open circuit voltage of solar PV module samples are analysed to further validate the influence of dust particles with various module surface temperatures.

## 3.2 Experimental method

In this section, the particle deposition experiment both for glass samples and actual solar PV module samples are introduced, including the detailed procedure of particle deposition process and results measuring process.

### 3.2.1 Experimental setup and materials for glass samples

In this experiment, instead of using actual solar PV modules, surface glass was selected to be tested because the dust accumulation process mainly happens between solar PV module surface glass and ambient air. Another reason for selecting glass samples is that the light transmittance can be easily measured and actual solar PV module sample is opaque due to the solar incident absorption of solar cells. So the commonly utilized type of glasses similar to the top framing cover of solar PV modules was used in this study. Each glass sample has the dimension of 10cm x 10cm x 2mm (thickness).

Moreover, the long-term operation of solar PV modules under strong solar irradiance can cause the significant temperature rise of the module surface glass. However, the temperature control of the solar PV module surface is quite challenge. In order to simulate the actual temperature difference between glass surface and its surrounding air, a heating plate was used to heat the glass and keep the surface temperature constant during the experiment. This heating plate can produce any surface temperature from room temperature to 350 °C with an accuracy within 1 °C, as shown in Figure 3.1. As mentioned above, the temperature difference can reach to 30 °C - 50 °C in the realist solar PV module condition. So the heating temperatures for the heating plate in our experiment were set from 20 °C -80 °C.

Figure 3.1 Heating plate.

In addition, the experimental setup consists of a test chamber and an airborne particle generator (PALAS GmbH, RBG 1000, Karlsruhe, Germany), as presented in Figure 3.2. The aerosol-related setup and procedure are similar to previous study of our group (H. Jiang, Lu, & Sun, 2011). The chamber with a dimension of 1 m x 0.6 m x 0.9 m was sprayed with anti-static layer on its inner surface, as presented in Figure 3.3.


Figure 3.2 Dust generator.

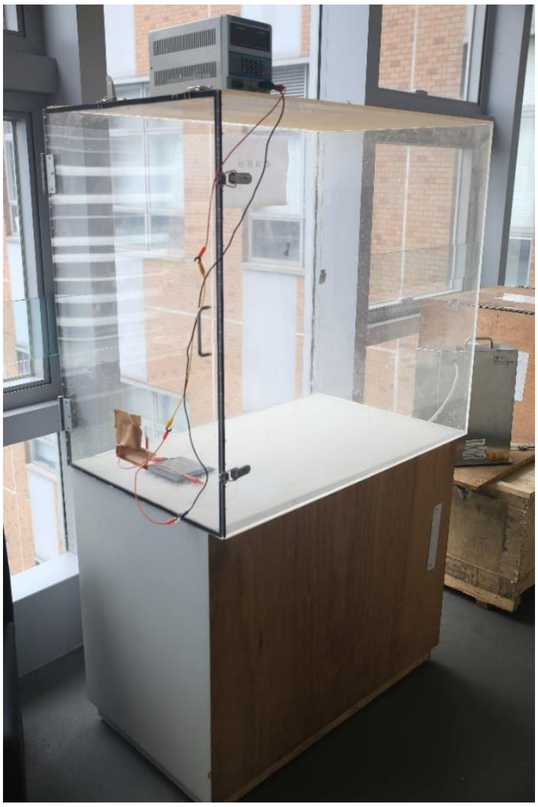


Figure 3.3 Experimental chamber.

Standard test particles were injected into the chamber by the particle generator and dispersed within the chamber. The Arizona test dust (Powder Technology Inc., 0–100 μm ATD, Minnesota, MN, USA) was chosen to act as the natural dry dust. Figure 3.4 shows the particle diameter distribution by volume percentage. The test dust particles are distributed in sizes between 1 μm to 100 μm. The volume of dust with a size of 20 μm is about 20%, and the sum volume of dust less than 20 μm is about 74%. Industrial dust is mainly composed of $SiO_2$ and $Al_2O_3$.

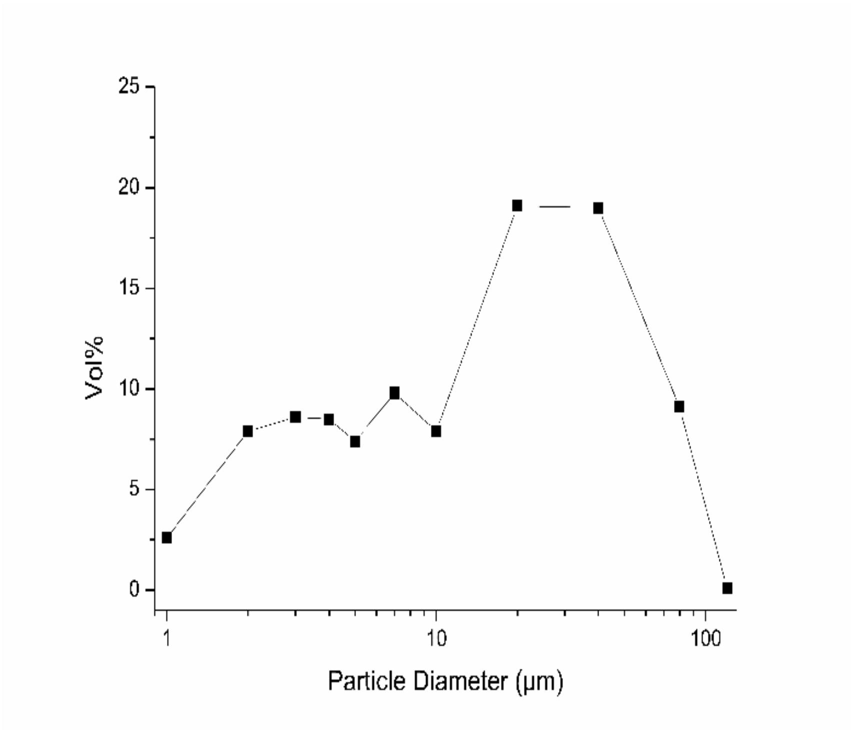



Figure 3.4 Dust size distribution by volume percentage.

### 3.2.2 Experimental procedure and protocol for glass samples

The experimental protocol for each dust deposition process in the chamber, balance weight and transmittance measurement was summarized as follows. Before the experiment, the temperature of the chamber was measured in order to set the proper temperature of heating plate to provide the expected temperature difference. In order to keep the dust deposition process in calm, the indoor air-conditioning system was turned off. Then, the heating plate was placed into the chamber with two glasses above. Two temperature sensors connected with one data logger measured and recorded the actual surface temperatures of glass samples and the ambient air temperature because the ambient temperature could be increased by the heating plate. When all the experimental facilities were well set, the aerosol generator was turned on to inject dust into the chamber for about 15 minutes. The aerosol particle would naturally deposit onto the sample glasses placed in the center floor of the chamber. So, after 24 hours, it can be assumed that the particle deposition process is completely finished. The heating plate was turned off, and the samples were cooled down with surface temperature reaching the room temperature. Then, the samples were sent to the indoor environmental quality laboratory (IAQ Lab) for dust weight measurement. The dust was measured by a high-accuracy digital microbalance (Precisa, Model 40SM-200A, 0.0001g) in a clean container, as shown in Figure 3.5. In the meantime, light transmittance data of the glass were similarly collected by a light meter (TENMARS, DL-201, 0.1) before and after dust deposition experiment to get the transmittance ratio. Identical processes were repeated for each scenario.

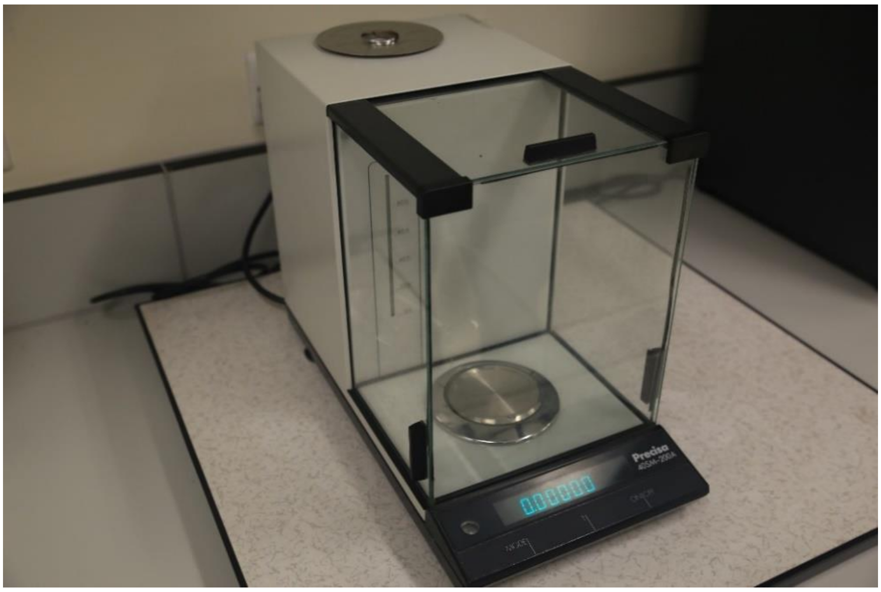



Figure 3.5 High-accuracy digital microbalance.

### 3.2.3 Experimental procedure and protocol for PV module samples

Two small identical monocrystalline silicon PV modules were chosen as test samples in this experiment, as presented in Figure 3.6. The modules were 135 mm × 135 mm which is the basic size unit adopted by common commercial solar cells in the commercial market.

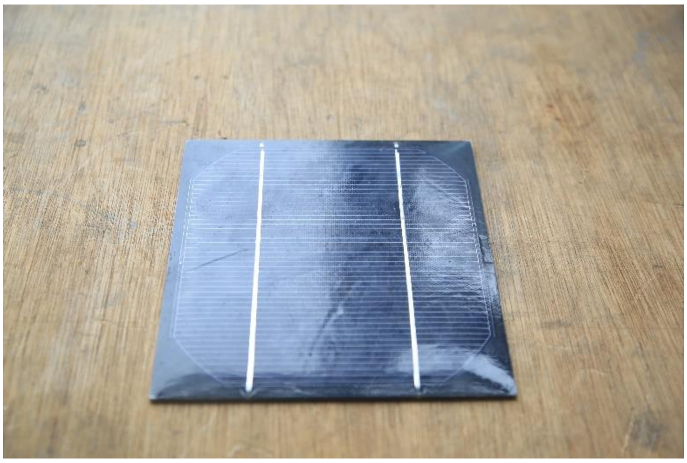


Figure 3.6 Solar PV module sample.

The experimental protocol for each aerosol deposition process in the chamber can be summarized as follows. Firstly, the heating plate was placed in the center of the chamber and test samples placed on the heating area. After the temperature of the surrounding air and the chamber were measured, the heating plate was then turned on. Two temperature sensors connected with one data logger measured and recorded the PV module actual surface temperatures and the ambient air temperature because the ambient temperature could be increased by the heating plate. Figure 3.7 illustrates the lab experimental apparatus. When the temperature difference had increased to the required level, the sensors were removed. In order to eliminate the effect of wind on particle deposition process, the indoor air-conditioning system and lights were turned off to ensure a dark and windless environment and to prevent the production of any small amount of heat by the PV samples under the room light. When all the experimental facilities were well established, the aerosol generator was turned on, and dust particles were injected into the chamber for about 20 min. Aerosol particles then deposited onto the test sample surface placed on the heating plate. To provide sufficient dust for the deposition process, the above injection procedure was repeated twice.

After 4 hours, the heating plate was turned off, and the PV samples cooled in a clean and tight container until the surface temperature reached the ambient temperature. The samples were then sent to an indoor environmental quality laboratory (IAQ Lab) for dust weight measurement. The dust was measured by a high-accuracy digital microbalance (Precisa, Model 40SM-200A, Dietikon, Switzerland, 0.0001g).

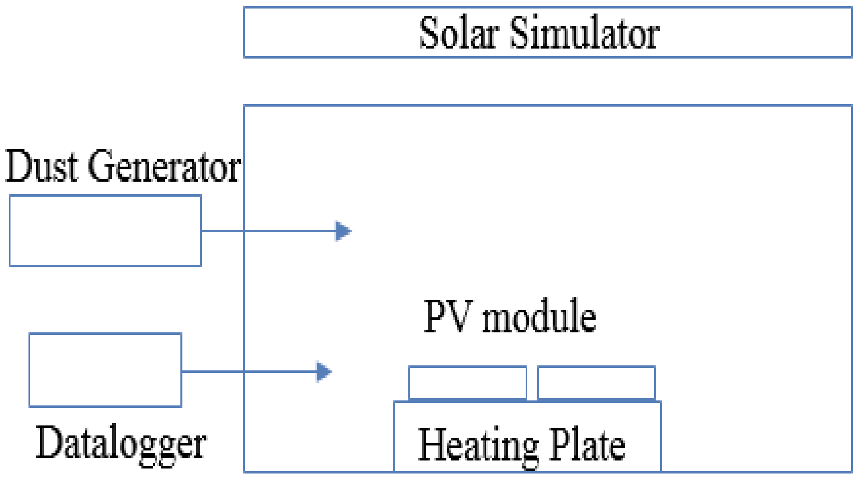



Figure 3.7 Illustration of lab experimental apparatus.

After the above procedure, the solar simulator (spectrum can be seen in Figure 3.8) was turned on, and the illumination intensity kept constant. PV modules were placed under the irradiation of the solar lamp, and the output power results were measured and analyzed by a MP-160 I-V Tracer (EKO Instruments, Tokyo, Japan). The accumulated dust was then cleaned away by a cloth, and the weight and the energy performance were recorded again as above. The heating temperature was then changed to provide a new required temperature difference and the whole process was repeated precisely for each temperature difference scenario.

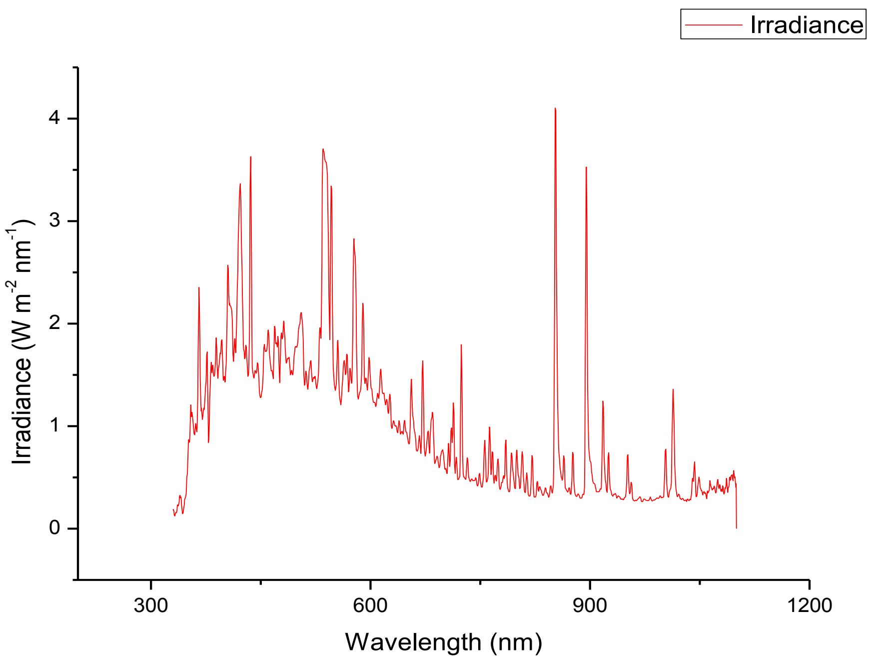



Figure 3.8 Light spectrum of the solar simulator.

## 3.3 Results for particle deposition on glass samples

The main results include three parts. The first part presents the effect of different temperature differences on dust accumulation process on glass samples. Secondly, the influence of different tilt angles is reported. Finally, light transmittance of glass samples is investigated. Details are presented as follows:

### 3.3.1 Influence of temperature differences

Figure 3.9 shows the results of dust deposition densities of glasses under different tilt angles (the angles between heating plate and tested samples) with various temperature differences between the heated tested samples and ambient air in the experimental chamber. Table 3.1 displays the uncertainty of the experimental measurement. It is obvious that particle deposition densities decrease with the increase of temperature differences. The particle deposition densities range from 0.19 $g/m^2$ to 0.05 $g/m^2$ on glasses when the temperature differences are from 0 to 60$^oC$, reducing approximately 75%. Actually, the density results are rather small, approximately one to three orders of magnitude, compared to those tests in the literature. This phenomenon can be explained. Firstly, the area of the sample is small, and dust particles may finally deposit on the other area of the chamber. Another reason for the relatively small deposition is the limited number of injection and short deposition period in our controlled experiments. If these glasses were exposed to fine particles as solar power modules or glazing windows for a long period, much more deposition and larger accumulation quantity can be obtained. In this experiment, the temperatures of the glasses placed on the heating plate are larger than the ambient temperature, and significant temperature gradients exist because of the temperature differences between glass samples and the ambient air. Thus, the thermophoresis can have an obvious effect on dust deposition process in significantly reducing dust deposition velocity.

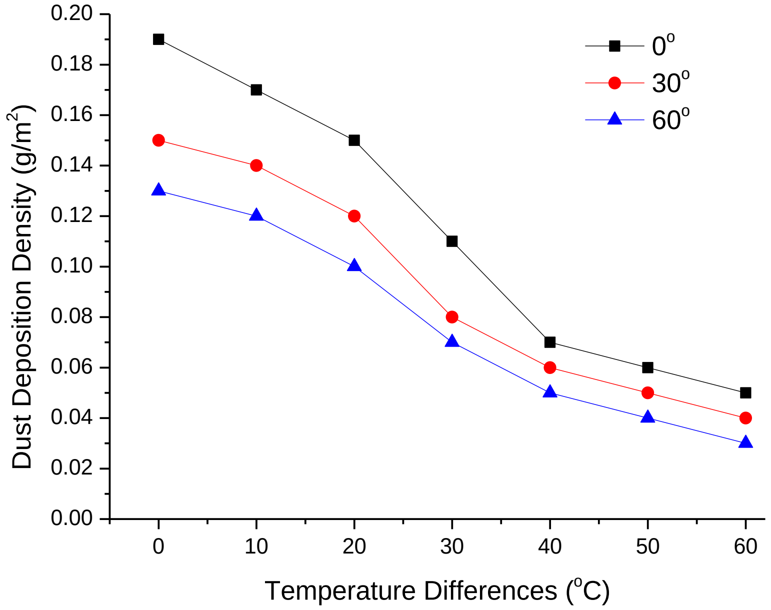



Figure 3.9 Dust deposition density with different temperature differences.

Table 3.1 Relative uncertainty of output parameters.

| Parameter | Relative Uncertainty |
|---|---|
| Dust deposition density | ±5% |
| Transmittance | ±7% |

### 3.3.2 Influence of tilt angles

Furthermore, the effect of the surface angle is examined by measuring the dust deposition densities under three different tilt angles increased from 0° to 60°, as presented in Figure 3.9. Apparently, the deposition densities decrease with the increase of tilt angles. The particle deposition density ranges from 0.03 to 0.19 g/m$^2$. The deposited aerosols roughly reduce about 17% from horizontally to 30$^o$ placed glasses. From the tilt angles of 30$^o$ and 60$^o$, the deposition density reductions are from 13% to 40% with average reduction of 20% for glasses. These phenomena are attributed to the aerosol gravity and aerosol-surface adhesion effect. As introduced before, although the tested dust is fine particle, they are subject to gravity when moving on the earth. When these dust deposit onto inclined surfaces, particles may roll or slide along the surface with the combined effect of gravity and aerosol-surface adhesion. Therefore, the deposition density with larger tilt angle surface is smaller than that with smaller one.

### 3.3.3 Effect of deposited dust on light transmittance

Light transmittance is another parameter to examine the dust deposition or dust accumulation on the surface. Generally, the higher dust deposition density means lower transmittance. To analyse effectively the light transmittance results of glasses with deposited aerosols, the "transmittance ratio" (*Tr*) is defined to describe the difference of glass light transmittance due to dust accumulation, as follows:

$$Tr = \frac{\text{light transmittance after aerosol deposition}}{\text{light transmittance before aerosol deposition}} \tag{3.1}$$

Higher transmittance ratios indicate less dust deposition on the glass.

As shown in Figure 3.10, the measured transmittance ratio ranges from 97.5% to 99.6%, and the transmittance reduction reaches 2.0% in the short experimental period. If the surfaces are exposed to the real atmosphere environment for several months or several years, the transmittance reduction can be significant. Besides, the transmittance ratio increases with the increase in surface temperatures, as well as the dust deposition density results. In addition to the effect of temperature differences, the transmittance ratio results also agree well with the dust deposition density in the effect of tilt angles on deposition process.

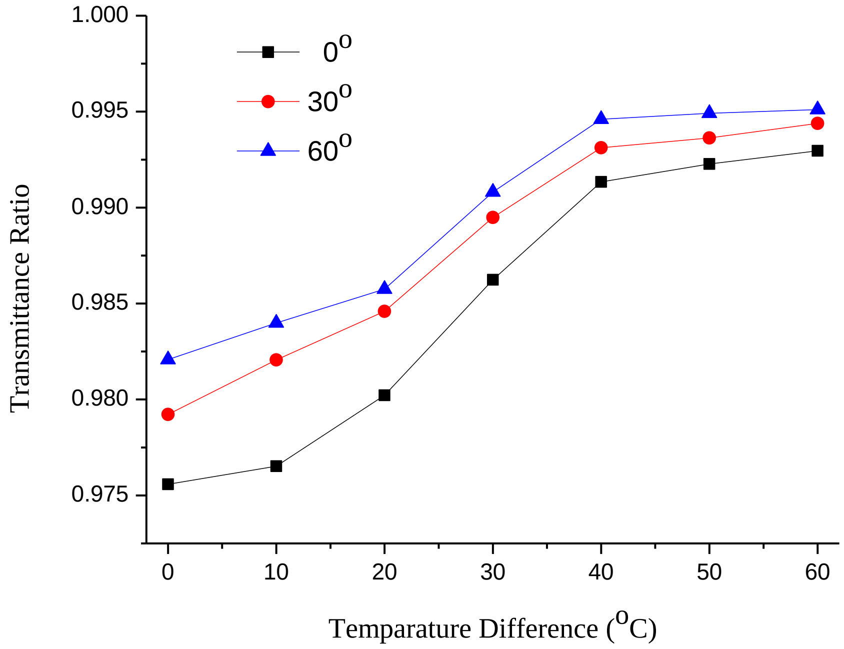



Figure 3.10 Transmittance ratio results with different temperature differences.

### 3.3.4 Deposition velocity due to temperature differences

As discussed above, the dust particle can move forward to the lower temperature area due to the effect of thermophoretic force. In fact, the fundamental cause of this force is the temperature gradient. Deposition velocity of dust particles can be presented as follows:

$$v = \frac{m}{C} \tag{3.1}$$

where $m$ is the deposition density; $C$ is the average concentration of the dust particle in chamber, which can be measured by TSI particle counter, as shown in Figure 3.11.


Figure 3.11 TSI dust tracker.

Thus, compared with deposition velocity with no temperature difference, the differences means the deposition velocity due to the thermophoretic force, which can be calculated as:

$$V_{th} = \frac{m_{no\ temperature\ difference} - m_{temperature\ difference}}{C \times Time} \tag{3.2}$$

In addition, a commonly used equation to describe the thermophoretic deposition velocity is shown as follows (Talbot et al., 1980):

$$V_{th} = \frac{6\pi d_p \mu^2 C_s (Km + C_t Kn)}{\rho(1+3C_m Kn)(1+2Km+2C_t Kn)} \frac{T_g - T_a}{m_p T_a} \tag{3.3}$$

Figure 3.12 presents the calculation results and experimental deposition results of horizontal surface position. Therefore, it can be found that the experimental results have the same tendency in comparison with the calculation results. However, it is obviously that the experimental results are drastically larger than calculation results because the actual average particle concentration in the ambient air during the experiment are drastically larger than the measured value. In addition, the air flow in this experiment is not fully developed which may affect the particle deposition density. The last reason is that particle deposition density is not the perfect method to measure particle deposition velocity because the movements due to experimenter can affect the measured results. Therefore, this equation can be applied to estimate the effect of temperature difference on dust accumulation process without cleaning effect of wind or rainwater.

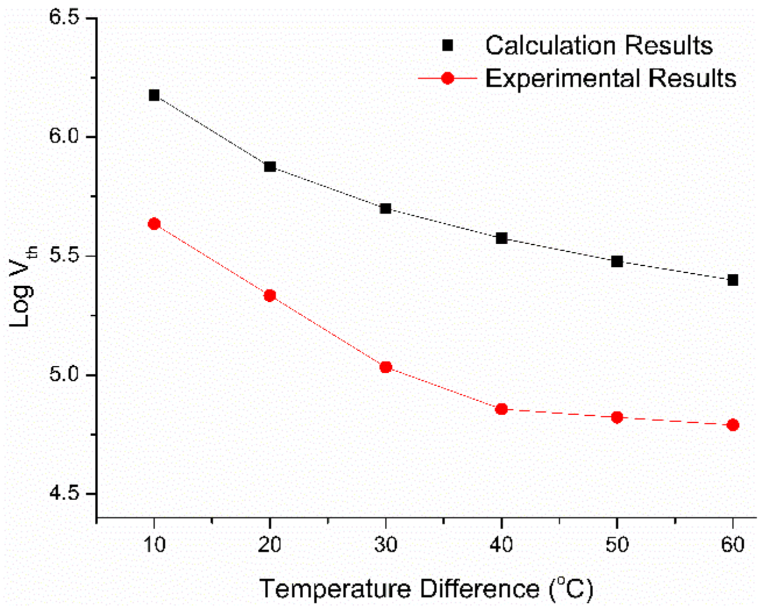



Figure 3.12 Thermophoresis deposition velocity under different temperature differences.

Moreover, this effect of temperature difference can help us to understand the efficiency reduction of PV modules in different weather conditions. El-Nashar (1994) proved that particle deposition densities are higher in summer by measuring the reduction of glass transmissivity. The surface temperature of PV module is higher than ambient air when the sunlight is sufficient at daytime. It means that dust deposition process mainly happens at night because the temperature of ambient air is higher and the direction of thermophoretic force is direct at PV module surface. In summer, the temperature difference is higher than that in winter at night. So the dust deposition densities are largest in summer night. So the differences in particle deposition densities between different seasons are contributed to the temperature gradient and the dust dominantly accumulates at night time.

## 3.4 Results for particle deposition on PV module samples

### 3.4.1 Densities of Deposited Particles

Table 3.2 presents the average deposited dust particle densities on the test silicon PV modules. Different temperature differences exist between the module and the surrounding air. The average particle deposition densities range from 0.54 $g/m^2$ to 0.85 $g/m^2$. When the surface temperature equals the surrounding air temperature, the deposited density is at its highest. Another significant finding is that particle deposition densities decrease with the increase in temperature difference. Hence, the module with the highest temperature difference has the lowest particle deposition density. The reason for this phenomenon is that the particle deposition process is influenced by a force, i.e., the thermophoresis force. This force is caused by the temperature difference between the PV module and its ambient air. In addition, the direction of the thermophoresis force is from the high temperature area to the low region. Thus, the thermophoresis force can drag particles from areas with higher temperatures to the zones with lower temperatures. There is no doubt that dust accumulation is less on a PV module surface when it is converting solar energy into utilized electric energy.

Table 3.2 Deposited dust particle densities for different temperature differences.

| Temperature Difference (℃) | Average Particle Deposition Density ($g/m^2$) | Relative Uncertainty |
|---|---|---|
| 0 | 0.85 | ±4% |
| 10 | 0.80 | ±8% |
| 20 | 0.73 | ±6% |
| 30 | 0.65 | ±4% |
| 40 | 0.58 | ±6% |
| 50 | 0.54 | ±3% |

### 3.4.2 Results of Power Performance

Due to the reduction of the deposited dust particles on PV modules, the output power of dirty and clean PV modules under a certain intensity of solar radiation is an important consequence. To compare the output power of the tested module effectively, the "output power ratio" ($\eta$) is defined to describe the difference of energy output due to dust accumulation, as follows:

$$\eta = P_A / P_C \tag{3.4}$$

where $P_A$ is the output power of a PV module with deposited dust particles, and $P_C$ is the output power of a clean PV module. As demonstrated in Figure 3.13, the output power of solar PV modules are various with the change of I-V curve and the MP-160 I-V Tracer used in this experiment can measure the maximum output power point, so $P_A$ means the maximum output power of PV module sample with accumulated dust and $P_C$ mans the maximum output power of clean PV module sample in this experiment.

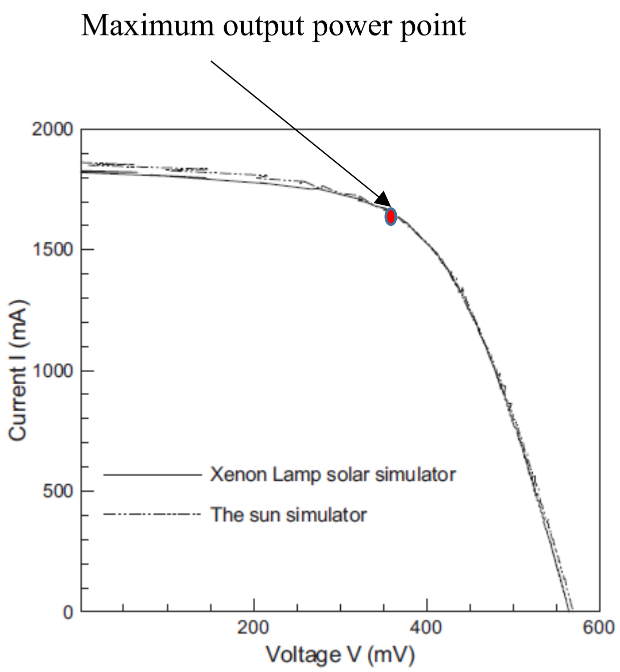



Figure 3.13 I-V curve of PV module sample under different solar simulator (H. Jiang et al., 2011).

Generally, a lower output power ratio means a reduction in output power due to deposited dust particles and higher dust deposition densities. Because the differences between the two identical test results were small, the results listed below and used in the figures are the averages of two samples.

Figure 3.14 and Table 3.3 present the output power results of the PV module studied for different imposed surface temperatures. Table 3.4 shows the relative uncertainty of the output parameters. In general, the output power ratios are found to range from 86.1% to 96.5%. Because the received solar radiation is different for each measurement, the curve in Figure 3.14 is up and down. For the clean PV module, it is obvious that output power is higher than the identical dusty one because dust particles can greatly reflect and absorb the available solar light and thus decrease the total received energy and the output power of the PV module, as shown in Figure 3.15. However, the power conversion efficiency of solar cells decreases due to the higher surface temperature. Hence, trying to use a thermal insulation coating to reduce the particle deposition density is not economic for solar power stations.

Table 3.3 Output power results for different temperature differences.

| Temperature difference ($^oC$) | Output power for dirty PV module (mW) | Output power for clean PV module (mW) | Output power ratio |
|---|---|---|---|
| 0 | 182.8 | 212.2 | 0.861 |
| 10 | 128.6 | 145.1 | 0.886 |
| 20 | 195.1 | 214.0 | 0.912 |
| 30 | 158.7 | 169.8 | 0.934 |
| 40 | 172.0 | 180.7 | 0.951 |
| 50 | 181.0 | 187.5 | 0.965 |

| Temperature difference (°C) | Short circuit current for dirty PV module (mA) | Short circuit current for clean PV module (mA) | Open circuit voltage for dirty PV module (mV) | Open circuit voltage for clean PV module (mV) |
|---|---|---|---|---|
| 0 | 701.8 | 855.3 | 558.0 | 557.1 |
| 10 | 708.9 | 739.3 | 554.8 | 552.2 |
| 20 | 704.0 | 714.2 | 561.4 | 558.4 |
| 30 | 729.0 | 753.2 | 561.3 | 555.8 |
| 40 | 687.7 | 728.1 | 553.5 | 552.8 |
| 50 | 727.9 | 753.8 | 552.0 | 557.9 |

Table 3.4 Relative uncertainty of output parameters.

| Parameter | Relative Uncertainty |
|---|---|
| Output power | ±7% |
| Short circuit current | ±9% |
| Open circuit voltage | ±3% |

For short circuit current and open circuit voltage of the tested module, Figures 3.16 and 3.17 present the results for all experimental temperature differences. For the short circuit current, the clean sample clearly produces higher currents. The reason is that the short circuit current is influenced by the received solar irradiation, and the deposited dust particles effectively reduce the solar incident light by reflecting and absorbing some of the incident energy.

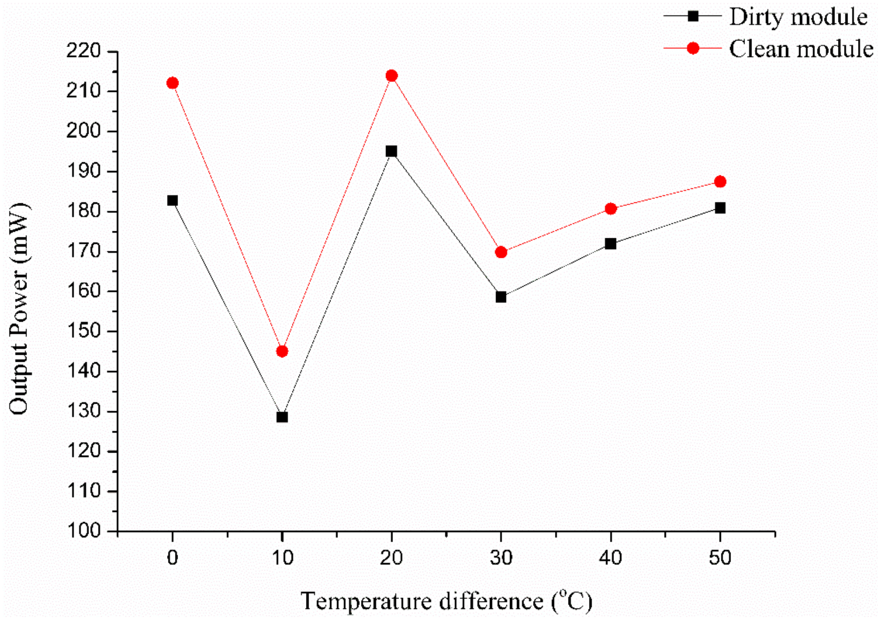



Figure 3.14 Output power results for different temperature differences (particle deposition densities with temperature difference are 0.85, 0.80, 0.73, 0.65, 0.58, and 0.54 g/m2 respectively).

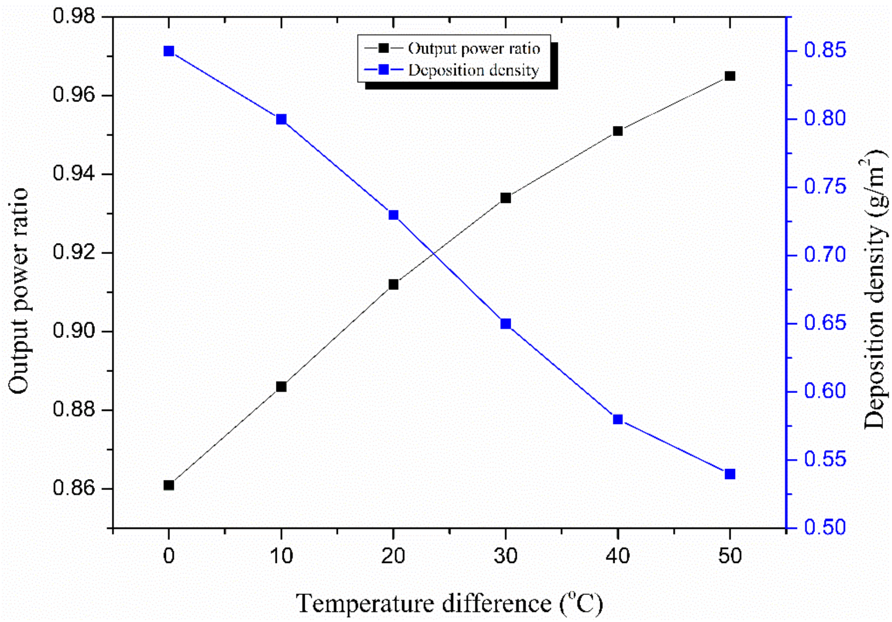



Figure 3.15 Output power results for different temperature differences (particle deposition densities with temperature difference are 0.85, 0.80, 0.73, 0.65, 0.58, and 0.54 g/m2 respectively).

However, the open circuit voltages are nearly the same for dirty and clean solar PV modules. Open circuit voltage depends highly on the temperature of the PV modules but not on the solar radiation intensity. In this experiment, the output of PV module's temperature was tested at room temperature; thus, the effect of deposited dust on the open circuit voltage can be neglected.

For engineers, to maintain a high energy output and conversion efficiency of PV modules, cleaning the accumulated dust on the surface of PV modules is important. As shown in this study, the higher temperature differences due to the heating leads to less particle deposition. Hence, during the day or in the summer, when the sun's radiation is sufficiently strong, engineers should take measures for cooling the high temperature to keep up a high energy conversion efficiency.

However, at night or in the winter, when the sun's radiation is weak, the accumulation velocity of dust particles is larger and engineers should clean more often, especially in desert areas where the accumulated dust is extremely high.

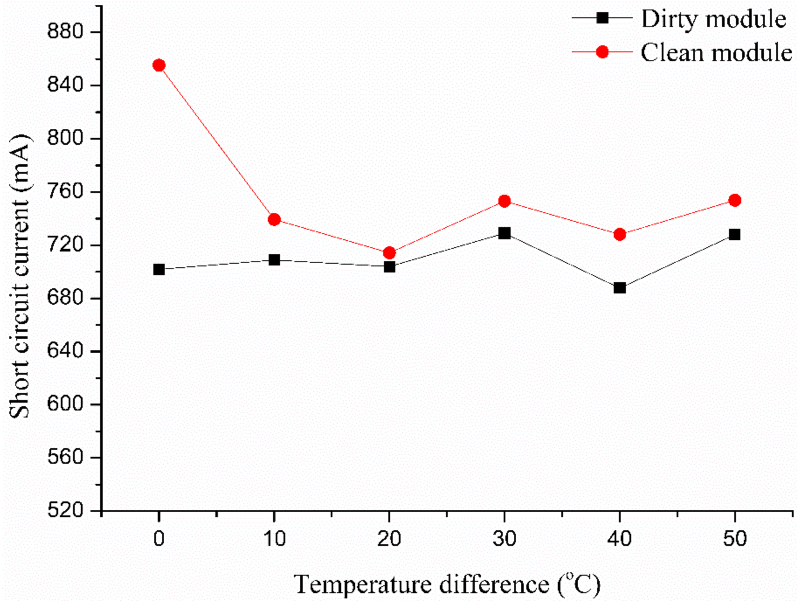



Figure 3.16 Short circuit current results under different temperature differences.

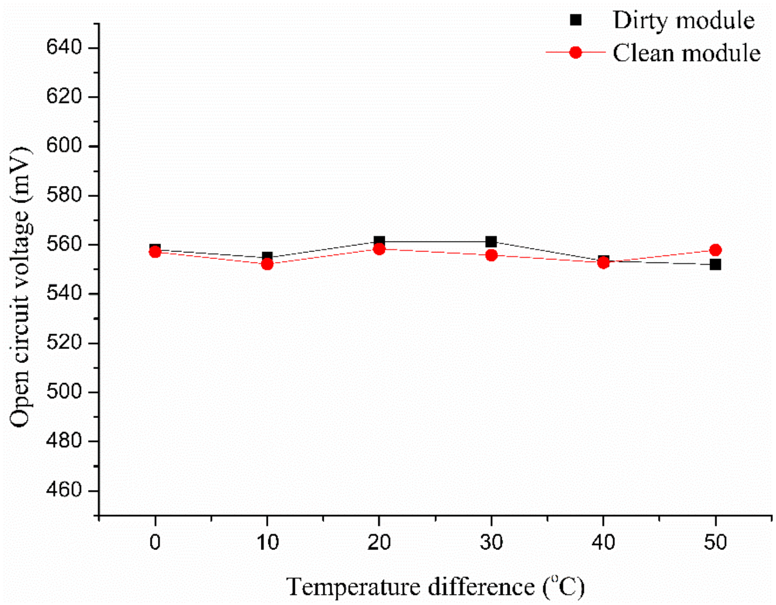



Figure 3.17 Open circuit voltage results with temperature differences.

## 3.5 Summary

This chapter experimentally studied the dust particle deposition onto glass samples to investigate the effect of temperature difference (thermophoresis) on dust accumulation process. The effects of different glass tilt angles were also investigated. Systematic experiments were designed in a test chamber to study the influence of distinct surface physical properties on fine aerosol accumulation and glass light transmittance. The major findings can be summarized as follows:

1) The measured deposition densities of fine aerosols are decreased from 0.19 to 0.05 $g/m^2$ when temperature differences increase from 0 to $60^o$, reducing nearly 75%. The glass with higher surface temperature has lower density due to the effect of thermophoresis arising from temperature differences.

2) Generally, the deposition densities decrease with the increase of sample tilt angles for all conditions due to the combination effect of aerosol gravity and aerosol surface adhesion.

3) The glass light transmittance ratios increase with the increase in temperature differences and tilt angles, ranging from 0.975 to 0.996 and increasing nearly 2% to show the decreased influence of temperature differences on dust accumulation process..

4) The experimental results have the same trend (decreasing) as the calculation results, so the Eq. (3.3) can be used to estimate the effect of temperature

difference on dust accumulation process on solar PV modules.

Even though a high temperature causes a significant reduction in energy conversion, a high temperature difference between the PV module surface and ambient air can decrease the dust accumulation on PV modules. This chapter also presents the experiments with PV module samples to investigate the effect of temperature differences of dust particle deposition on solar PV modules. The main findings are summarized as follows:

1) The measured deposition densities of fine particles ranged from 0.54 g/m$^2$ to 0.85 g/m$^2$ under the experimental conditions. The PV module with a higher surface temperature experienced a lower dust density due to the effect of thermophoresis arising from the temperature difference.

2) The maximum output power ratios increased from 0.861 to 0.965 with an increase in temperature difference from 0 to 50 °C, increasing approximately 12.1%. The results also show a similar dust deposition trend due to the thermophoresis force resulted from existed temperature gradient in particle deposition process.

3) Dust particles have a significant impact on the short circuit current and the output power of PV modules. However, the influence of particle on the open circuit voltage can be negligible.

In summary, for the operating solar PV modules, the temperature of solar cells or modules will increase dramatically, which will reduce the module power conversion efficiency and its power output. However, at the same time, this higher temperature can cause some offsetting output improvement by decreasing the power reduction effect caused by deposited dust particles on PV modules through the reduction of the surface accumulation of dust particles due to thermophoresis.

Apart from the temperature differences of operational PV modules, the influence of generated current for operational solar PV modules is never examined. So, the next chapter will present the effect of generated current of operational solar PV modules from energy conversion on dust accumulation process.

# CHAPTER 4 INFULENCE OF GENERATED CURRENT AND CORRESPONDIND ELECTROSTAYIC FORCE ON DUST ACCUMULATION ON PV MODULES

## 4.1 Introduction

As mentioned in Chapter 2, in addition to temperature differences between the solar PV covers and the ambient air, another characteristic of operating solar PV modules is the generated current due to photovoltaic effect of solar cells. However, there is no report about this effect of generated current on dust accumulation process. So, the objective of this chapter is to newly investigate the influence of generated current on dust particle deposition process on solar PV module surface.

In this section, particle deposition experiments which are similar to the experiments for the study of influence of temperature differences have been conducted in order to illustrate the influence of generated current on dust accumulation process for solar PV modules. Deposition density results for different provided currents are measured in this chapter. In addition, the theoretical model for different mechanisms of electrostatic force, such as Columbic force due to electric field by generated current and image force due to the interaction between charged particles and deposited surface, is presented and the impact of significant parameters on this two different electrostatic forces are analysed.

## 4.2 Research method

Actual small solar PV module samples were chosen to be the tested samples because the dust accumulation process mainly happened between solar PV module covers and ambient air. The generated current can be easily simulated. Each small solar PV module sample has the dimension of 135 mm x 135 mm x 2 mm (thickness), as shown in Figure 4.1. In order to simulate the current generated due to the photovolatic effect of solar cells with sufficient solar radiation, a DC power supply (DPS-305BM) was used to continuously provide required current during this experiment, as shown in Figure 4.2. The current used in this experiment ranged from 0 to 5A because the maximum current for operating solar PV modules is generally less than 6A. In addition, the experimental rig consists of a test chamber and an airborne particle generator. The aerosol-related setup and procedure are similar to those adopted in the previous chapter. The chamber with a dimension of 1 m x 1 m x 0.6 m was sprayed with anti-static layer on its inner surface. Standard test particles were injected into the chamber by the particle generator (PALAS GmbH, RBG 1000, Karlsruhe, Germany) and dispersed within the chamber. The Arizona test dust (Powder Technology Inc., Nominal 0-100μm ATD, Burnsville, Minnesota, USA) was used in this work in order to fit the size distribution, shape and chemical components of the natural dry dust particles.

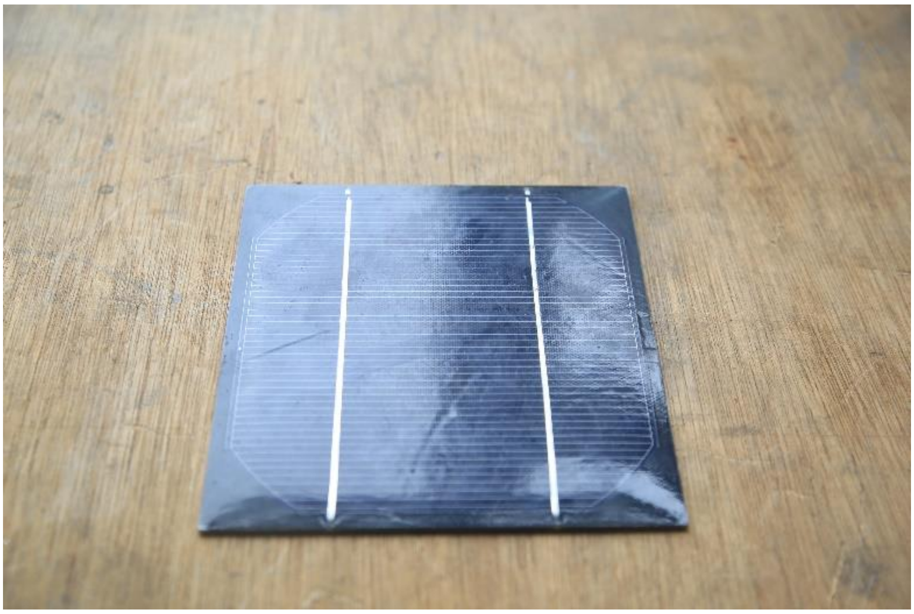


Figure 4.1 Solar PV module sample.


Figure 4.2 DC power supply for deposition experiment.

The experimental protocol for each aerosol deposition process in the chamber, balance weight and transmittance measurement are summarized as follows. In order to keep the chamber aerosol deposition in calm, the indoor air-conditioning system was turned off. Then, the DC power supply was turned on with two solar PV module samples to continuously provide current which simulates the generated current owing to the photovoltaic effect of solar cells under sufficient solar radiation. When all the experimental facilities were well set, aerosol generator was turned on to inject dust into the chamber for about 15 minutes. The aerosol particle would naturally deposit onto the solar PV module sample placed in the center floor of the chamber. After 4 hours, the electrical power supply was turned off. Then, the samples were sent to the indoor environmental quality laboratory (IAQ Lab) for dust weight measurement. The dust was measured by a high-accuracy digital microbalance (Precisa, Model 40SM-200A) in a clean container. Identical processes were repeated for each scenario.

## 4.3 Results

In this section, particle deposition density results are firstly introduced and the reason is preliminarily explained. Then, different types of electrostatic forces are summarized and impact of significant parameters on Columbic force and image force are analysed respectively.

### 4.3.1 Particle deposition density with different currents

Figure 4.3 shows the particle deposition density results for actual solar PV module samples with different provided currents from 0 to 5A. The deposition densities ranging from 0.17 g/m$^2$ to 0.41 g/m$^2$ are decreased with the decrease of provided current, nearly decreasing 50%. Therefore, is can be concluded that generated current can increase the accumulation velocity of dust on solar PV module surface.

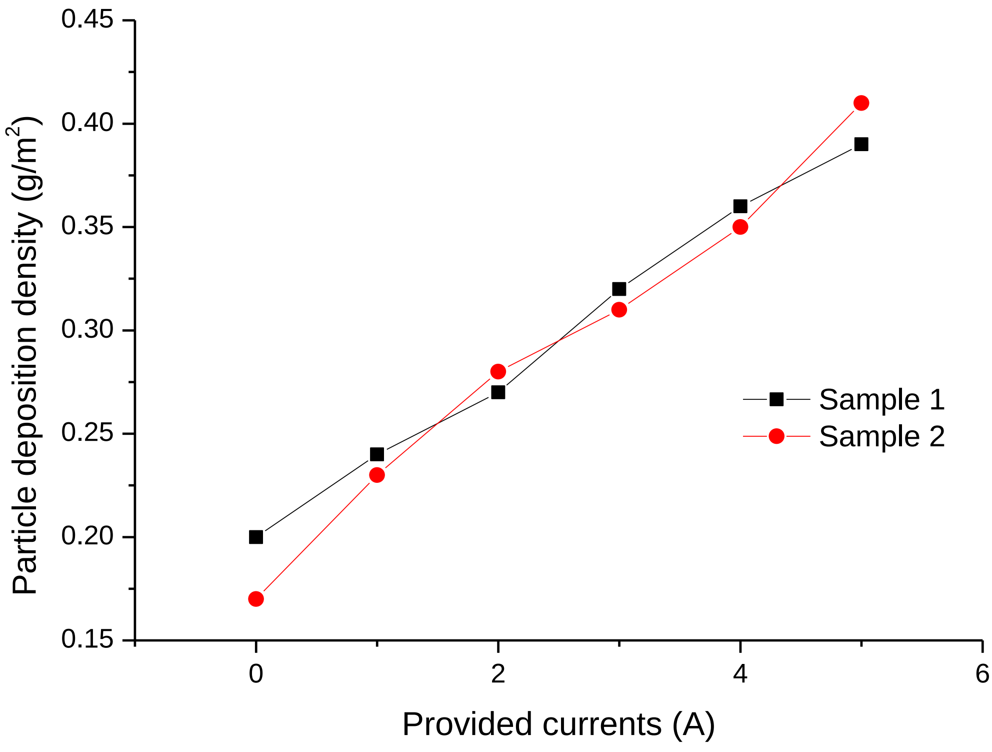



Figure 4.3 Particle deposition densities for different currents.

The reason for this phenomenon is that the generated current can lead to an electric field near the PV module surface. When dust particles flow into this electrical field area because of the gravity, it subjected to the electrostatic force due to this generated electrical field. Electrostatic force contains four kinds of forces for dust deposition process. One is Coulombic force, which is happened when charged particles are located in the induced electric field owing to the generated current, can be calculated by

Coulombic Law. The other one is image force, which means a charged particle of charge q and a conducting surface. In addition to these two main forces of electrostatic force, the dielectrophoretic force and the dipole–dipole force, are usually neglected when compared with the previous two forces.

### 4.3.2 Electrostatic force for particle deposition process

#### 4.3.2.1 Coulombic force

As introduced in previous section, the Coulombic force and the image force are dominating in electrostatic force for particle deposition process. Particle deposition velocity due to Coulombic force can be expressed as:

$$v_e = \frac{neE}{f} \tag{4.1}$$

where $n$ is the number of elementary charges on the deposited particle, $e$ is the elementary charge and equals $1.602\times10^{-19}$ C, $E$ is the electric field of the deposition direction. In addition, $f$ means the drag coefficient and can be calculated by Stork's law as:

$$f = 3\pi\mu d_p / C_c \tag{4.2}$$

where $\mu$ is the dynamic viscosity of air, $d_p$ is the particle diameter and $C_c$ means the Cunningham correction factor and can be expressed as:

$$C_c = 1 + Kn\left[1.257 + 0.4\exp(-1.1/Kn)\right] \quad (4.3)$$

where $Kn$ is the Knudsen number and equals to the ratio of mean free path of the fluid to particle radius.

#### 4.3.2.2 Image force

Image force is present between a charged particle of charge q and a conducting surface (corresponding to the force exerted by an image charge of −q at position −y from the surface, supposing that the particle is y away from the surface).

So, the particle deposition velocity due to image force can be expressed as:

$$v_i = \frac{K_E n^2 e^2}{4f} \Phi(\varepsilon) \frac{1}{y^2} \quad (4.4)$$

where $K_E$ is the electrostatic constant of proportionality and equals to $9.0\times10^9$ $N\cdot m^2/C^2$. $\Phi(\varepsilon)$ means the dielectric constant factor and can be determined as:

$$\Phi(\varepsilon) = \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1} \quad (4.5)$$

where $\varepsilon_1$ and $\varepsilon_2$ are the dielectric constant of local air and surface material, respectively. For dry air, $\varepsilon_1 \cong 1$. In addition, for surface materials with perfect insulators, $\varepsilon_2 = 1$ and then $\Phi(\varepsilon) = 0$. In this case, particle deposition process is not influenced by image force. However, for perfect conductor materials, $\varepsilon_2 = \infty$ and then $\Phi(\varepsilon) = 1$. In this case, the image force is largest. Unlike the Columbic force, the direction of image force is always towards to the deposited surface.

#### 4.3.2.3 Particle charge distribution

As shown in Eq. (4.1) and Eq. (4.4), particle deposition velocity due to Columbic force or image force is greatly dependent on the number of elementary charges on particle. In fact, there are two charging mechanisms, Boltzmann charge equilibrium mechanism and diffusion and field charging mechanism.

Boltzmann equilibrium means that particles in a bipolar ionic fluid can form an equilibrium charge state. One common equation for average number of charges can be used when particle diameter is larger than 0.2 μm, as:

$$n_{ave} = 2.37\sqrt{d_p} \quad (4.6)$$

Besides, particles mixed with unipolar ions can be charged owing to the random collisions between the ions and the particles due to the Brownian motion. For particles less than 1 μm, diffusion charging is the most obvious charging mechanism.

Finally, in case of strong electric field, field charging means that particles are charged by frequent collisions with unipolar ions in rapid motion. Compared with diffusion charging mechanism, field charging mechanism is more significant for particles which diameters are larger than 1 μm.

Table 4.1 Particle charging number due to different mechanisms for various diameters (F. Chen & Lai, 2004).

| Particle diameter (μm) | Boltzmann equilibrium | Diffusion charging | Field charging |
|---|---|---|---|
| 0.01 | 0.24 | 0.276 | 0.0007 |
| 0.02 | 0.34 | 0.671 | 0.0028 |
| 0.05 | 0.53 | 2.08 | 0.0174 |
| 0.1 | 0.75 | 4.77 | 0.0694 |
| 0.2 | 1.06 | 11 | 0.277 |
| 0.5 | 1.68 | 31 | 1.74 |
| 1 | 2.37 | 68 | 6.94 |
| 2 | 3.35 | 149 | 28 |
| 5 | 5.30 | 412 | 174 |
| 10 | 7.49 | 886 | 694 |

Table 4.1 presents the particle charge distribution of above three different mechanisms for various diameters (F. Chen & Lai, 2004). Firstly, larger particle can have induced charging number due to all charging mechanisms because larger particle has more elementary charge. It is obvious that Boltzmann equilibrium charging leads to the minimum number for all particle diameters. In addition, influence of diffusion charging is significant, especially for small particles. However, even the charging effect of field charging is not apparent, field charging greatly results in larger numbers of charged particles with the increase of particle diameters.

#### 4.3.2.4 Particle deposition velocity due to Columbic force

Based on Eq. (4.1) and particle charge distribution from Table 4.1, particle deposition velocity due to Columbic force can be accurately calculated. To analyse the effect of key parameters including particle diameter and electric field intensity on this deposition mechanism, three different electric fields from 10 V/m to 1000V/m and various particle diameters ranging from 0.01 μm to 10 μm were selected for calculation process. To clearly show the impact of different parameters on deposition velocity due to Columbic force, deposition velocity owing to image force is not considered in this section.

As presented in Figure 4.4, the calculated particle deposition velocity due to Columbic force under strong electric field based on Eq. (4.1) ranges from $7.34\times10^{-7}$ m/s to $3.12\times10^{-4}$ m/s for different particle diameters. It can be seen that particle deposition velocity is decreased with the increase of particle size firstly and then increased. Taking one electric field (100 V/m) for example, when particle diameters increase from 0.01 μm to 0.5 μm, deposition velocity decreased nearly 75% from $3.12\times10^{-5}$ m/s to $7.34\times10^{-6}$ m/s because small particle is significantly influenced by Columbic force when compared with large particle in this size range. However, when particle diameters increase from 0.5 μm to 10 μm, the deposition velocity due to electric field is greatly increased by 100% from $7.34\times10^{-6}$ m/s to $1.51\times10^{-5}$ m/s. It means that compared with small particle, large particle tends to be easily deposited into the deposited surface because of large particle charging number, especially due to field charging.

Additionally, when electric field decreases from 1000 V/m to 10V/m, it is obvious that particle deposition velocity approximately decreases by 99%, which is also presented in Figure 4.4. It can be found that deposition velocity by electric force is proportional to the level of electric field, as illustrated in Coulomb's Law by Eq. (4.1). Then, it can be concluded that the influence of generated current on dust accumulation process is great when sunlight is sufficient because solar PV modules can result in large current and corresponding electric field.

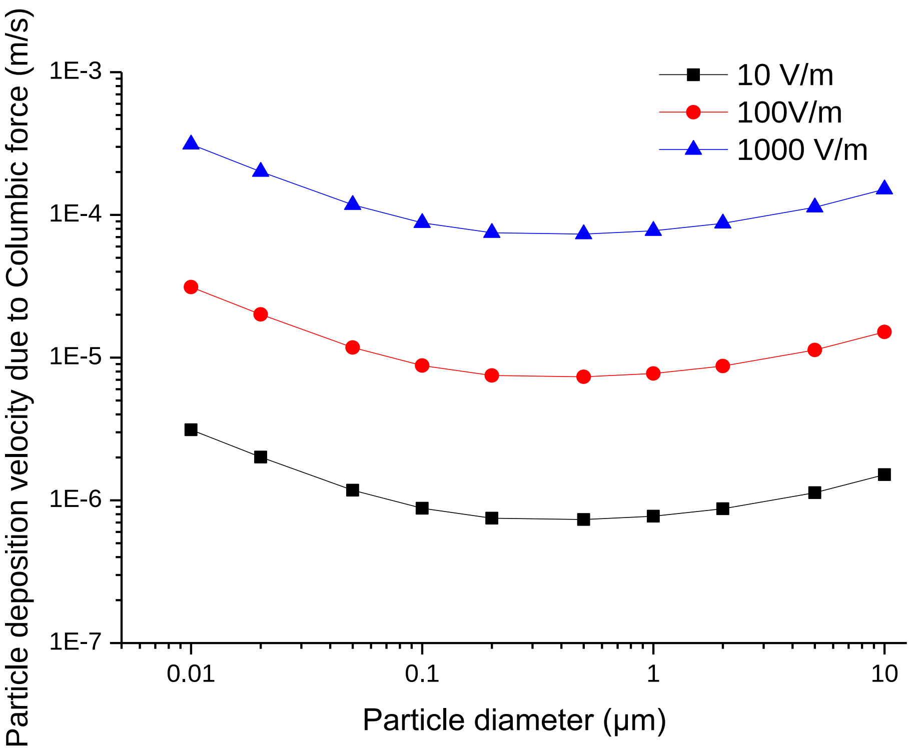



Figure 4.4 Particle deposition velocity due to Columbic force for different diameters under strong electric field.

#### 4.3.2.5 Particle deposition velocity due to image force

Similar to the previous calculation method, particle deposition velocity due to image force can be accurately calculated based on Eq. (4.4) and particle charge distribution from Table 4.1. To analyse the impact of key parameters on particle deposition velocity by image force, three different $\varepsilon_2$ (2, 5 and 10) and various particle diameters from 0.01 μm to 10 μm are selected for calculation. In addition, $y$ equals 1000 μm. In this case, the electric field strength is assumed to be zero to eliminate the impact of Columbic force by electric field.

Figure 4.5 shows the caused particle deposition velocity due to image force under different surface materials with various $\varepsilon_2$ and particle parameters. It is clear that the deposition velocity of image force is increased with the increase of particle diameters. This is mainly because deposition velocity of image force is proportional to the particle charge level and large particle has large particle charging number based on diffusion charging mechanism. In addition, the deposition velocity also increases with the increase of dielectric constant. So, the image force has great effect on the surface material with large dielectric constant.

Additionally, compared with deposition velocity due to Columbic force, it is apparent that the caused deposition velocity due to image force is too small. Hence, the deposition velocity due to image force can be neglected in analysing dust accumulation process on operating solar PV modules because of the significant differences in value of deposition velocity caused by Columbic force or image force.

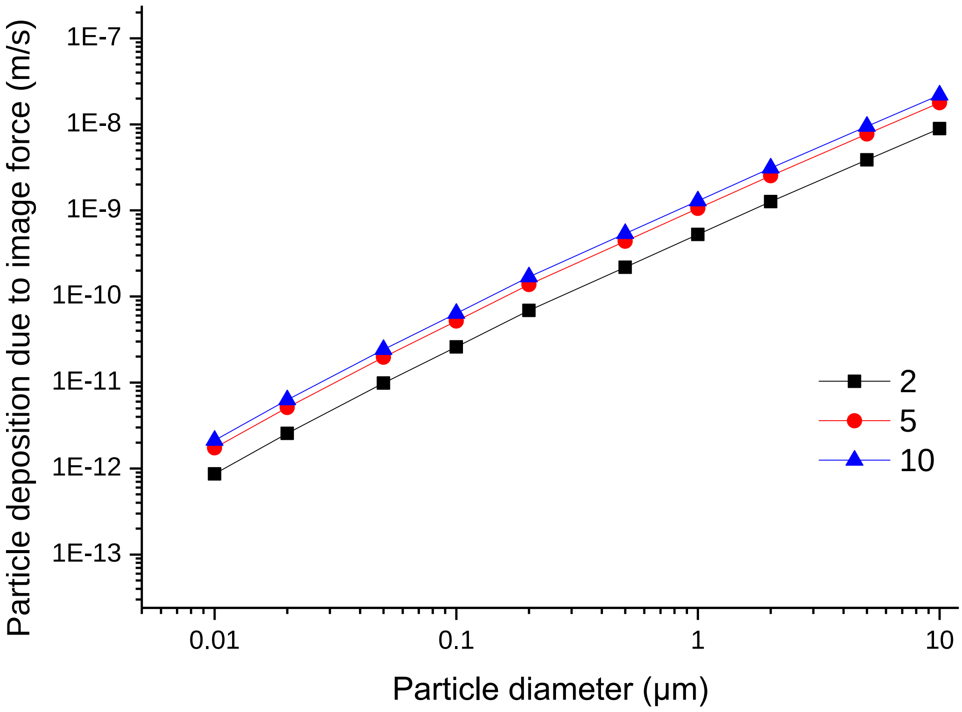



Figure 4.5 Particle deposition velocity due to image force for different diameters under various dielectric constants.

## 4.4 Summary

In this chapter, particle deposition experiments were conducted in a designed chamber which was similar to that described in Chapter 3 to investigate the influence of generated current due to the energy conversion process of solar PV modules on dust accumulation process. The generated current of operating solar PV modules was simulated by voltage power supply. In addition to particle deposition experiment, the particle deposition velocity due to electrostatic force was theoretically studied by different mechanisms, including Columbic force due to strong electric field and image force due to particle movements. Main findings are presented as follows:

1) The deposition density ranged from 0.17 $g/m^2$ to 0.41 $g/m^2$ for different module currents, and increased with the increase of provided currents. The reason for this is that dust particles result from the generated electric field due to the generated current.

2) The particle deposition velocity depends on particle size and charge level, turbulent intensity, electric field strength and surface material. The Coulombic force plays an important role in particle deposition for the operating solar PV modules. For particles at extremely high charge level and in the presence of a strong electric field, the Coulombic force contributes significantly by enhancing deposition of accommodation mode particle size. The image force is important when the particle charge level is high and the electric field strength is weak.

3) The calculated particle deposition velocity due to Columbic force under strong electric field based on Eq. (4.1) ranges from 7.34×10-7 m/s to 3.12×10-4 m/s for different particle diameters. When particle diameters increase from 0.01 μm to 0.5 μm, deposition velocity decreased nearly 75% from $3.12\times10^{-5}$ m/s to $7.34\times10^{-6}$ m/s because small particle is significantly influenced by Columbic force when compared with large particle in this size range. However, when particle diameters increase from 0.5 μm to 10 μm, the deposition velocity due

to electric field is greatly increased 100% from $7.34\times10^{-6}$ m/s to $1.51\times10^{-5}$ m/s because large charging numbers for large particles.

4) Deposition velocity of image force is increased with the increase of particle diameters because deposition velocity of image force is proportional to the particle charge level and large particle has large particle charging number based on diffusion charging mechanism. In addition, deposition velocity is also increase with the increase of dielectric constant.

So, the influences of characteristics of operating solar PV modules on dust accumulation process, both temperature differences and generated current, have been studied based on indoor particle deposition experiments and theoretical model. However, cleaning issues of dust accumulation are important to maintain the high energy conversion efficiency of solar PV systems, especially for large scale solar PV plants. Therefore, natural cleaning process owing to wind and reasonable cleaning frequency in desert areas are presented in the next two chapters.

# CHAPTER 5 ANALYZING WIND CLEANING PROCESS ON DUST ACCUMULATION ON SOLAR PHOTOVOLTAIC (PV) MODULES REGARDING PARTICLE RESUSPENSION

## 5.1 Introduction

After investigating the influence of temperature differences and generated current owing to energy conversion process of PV modules on dust accumulation on PV surface, referring to the discussion in Chapter 2, even though the cleaning effect of wind on dust accumulation on PV modules has been reported, the details of this process were seldom examined. Therefore, it is difficult to evaluate the performance of wind cleaning process for dust accumulation because there is no reported model to calculate the required wind velocity for particle removal and the influence of various dust particle sizes and compositions.

So, the main objective of this chapter is to build a theoretical model to describe the wind cleaning process for deposited dust particles on PV modules. This model is a particle resuspension model for one particle attached to a flat surface and the minimum shear velocity (and the corresponding actual wind velocity) that can re-suspend dust particles from solar PV module surface is evaluated. Both smooth and rough spherical particles are studied. In addition, based on this developed resuspension model, the difficulty of different compositions of deposited dust particles for removal by wind is compared according to the calculated minimum shear velocity of different diameters from 0.1 μm to 100 μm.

## 5.2 Development of resuspension model for particle removal

The wind cleaning process of deposited particles can be regarded as a resuspension process that the deposited dust particles are detached from the PV module surface due to the hydrodynamic force arising from the airflow. Therefore, to analyze the wind cleaning process, a novel model is developed based on the particle resuspension theory. The minimum shear velocity and the corresponding actual wind velocity for detaching rough and smooth spherical particles with a specific diameter are evaluated. The rolling model for particle resuspension, including particle adhesion force and hydrodynamic forces and torque, was used in the model.

Figure 5.1 shows the schematic of a spherical particle on a flat surface and the corresponding hydrodynamic drag force and the moment acting on the particle. Based on this rolling detachment model, the particle is removed if the removal moments are larger than the resistant moments (Soltani & Ahmadi, 1994). That is the resuspension occurs if:

$$M_h + F_h \frac{d}{2} \geq F_{po}^{Rough} a_{Rough} \quad (5.1)$$

where $M_h$ is the hydrodynamic torque acting on a spherical particle attached to a surface, $F_h$ is the hydrodynamic drag force acting on a small spherical particle in the viscous sublayer of a turbulent flow, $d$ is the particle diameter, $F_{po}^{Rough}$ is the pull-off force for a rough spherical particle from a rough surface and $a_{Rough}$ is the contact radius for rough particles.

So, as $M_h$ and $F_h$ can be expressed as the function of actual wind velocity $U_\infty$ (presented in next section), the minimum wind velocity for particle resuspension can be calculated based on Eq. (5.1).

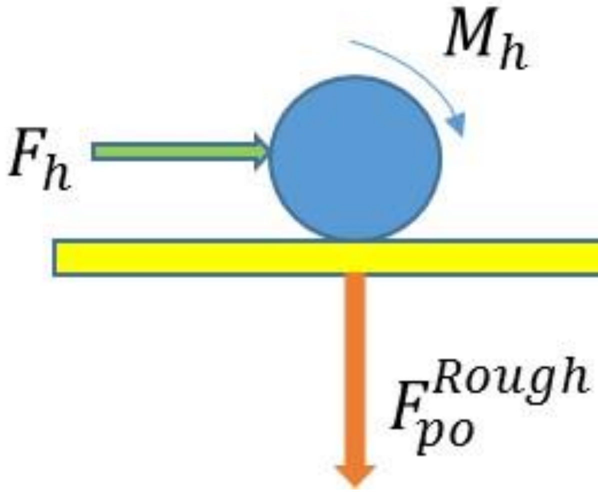



Figure 5.1 Schematic of particle resuspension by the rolling model detachment process.

### 5.2.1 Adhesion model for pull-off force $F_{po}^{Rough}$ of rough, spherical particles

The JKR adhesion model for describing the adhesion force between spherical particles and a flat surface, was developed by including the influence of surface energy on the particle-surface contact area (Johnson, Kendall, & Roberts, 1971). Accordingly, the contact radius, $a_{JKR}$, can be calculated as:

$$a_{JKR} = \frac{d}{2K}\left[P + \frac{3}{2}W_a \pi d + \sqrt{3\pi W_a dP + (\frac{3\pi W_a d}{2})^2}\right] \tag{5.2}$$

where $d$ is the particle diameter, $P$ is the external force and $W_a$ is the thermodynamic work of adhesion of particle-surface contact. $K$, the composite Young modulus, and is given as:

$$K = \frac{4}{3}\left[\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}\right]^{-1} \tag{5.3}$$

where $v_1$ and $v_2$ are the Poisson ratio for particle and substrate, respectively. Similarly, $E_1$

and $E_2$ are the Young modulus for particle and substrate, respectively.

The pull off (removal) force for detaching a particle from the surface according to the JKR model is given as:

$$F_{po}^{JKR} = \frac{3}{4}\pi W_a d \tag{5.4}$$

At the time of separation, the contact radius is given as:

$$a_{JKR} = \left( \frac{F_{po}^{JKR} d}{2K} \right)^{\frac{1}{3}} \tag{5.5}$$

However, for real particles, the presence of surface roughness is inevitable. The roughness of particle significantly decreases the effective adhesion force. This is because the surface roughness greatly decreases the real contact area between the particles and the substrate.

Including the effect of surface roughness of particles and surface, an expression for the removal force for removing rough spherical particles from a flat surface was developed (Fuller & Tabor, 1975; Soltani & Ahmadi, 1994, 1995b). Accordingly, the pull off force is given as:

$$F_{po}^{Rough} = \pi a_{Rough}^2 n f_{po} \exp(\frac{-0.6}{\Delta_C^2}) \tag{5.6}$$

where

$$a_{Rough} = (\frac{F_{po}^{Rough} d}{2K})^{1/3} \tag{5.7}$$

and $f_{po} = 1.5\pi W_a \beta_r$ (5.8)

where $n$ is the number of asperities of per unit area, $a_{Rough}$ is the contact radius for rough particles, $f_{po}$ is the adhesion force for each asperity from calculation results of JKR adhesion model, $\Delta_C$ is the non-dimensional roughness parameter and $\beta_r$ is the radius of each contact asperity.

It is assumed that if the non-dimensional roughness parameter $\Delta_C$ is sufficiently large, the surface can be regarded as smooth, and the pull off force given by Eq. (5.6) equals the adhesion force of the JKR model (Goldasteh, Ahmadi, & Ferro, 2013). Accordingly, the number of asperity per unit area can be estimated as:

$$n = (\frac{0.0029K^2}{dW_a^2\beta_r^3})^{\frac{1}{3}} \quad (5.9)$$

The corresponding contact radius of sphere with surface roughness is given as:

$$a_{Rough} = \frac{\pi n f_{po} d \exp(\frac{-0.6}{\Delta_C^2})}{2K} \quad (5.10)$$

Using the contact radius for rough surface as given by Eq. (5.10), the pull-off force for a rough spherical particle from a rough surface based on Eq. (5.6) is given as:

$$F_{po}^{Rough} = (\frac{d}{2K})^2[1.5nW_a\beta_r\pi^2 \exp(\frac{-0.6}{\Delta_C^2})]^3 \quad (5.11)$$

### 5.2.2 Hydrodynamic force and torque in turbulent flow

The hydrodynamic drag force acting on a small spherical particle in the viscous sublayer of a turbulent flow can be expressed as (Ahmadi & Guo, 2007):

$$F_h = \frac{C_D \pi f \rho d^2 u_M^2}{8C_c} \quad (5.12)$$

where $\rho$ is the fluid density, $u_M$, the fluid velocity at the center of particle and $f$, the correction factor due to the wall effect, equals to 1.7009 (O'neill, 1968). $C_c$, the Cunningham correction factor, can be expressed as:

$$C_c = 1 + Kn\left[1.257 + 0.4\exp(-1.1/Kn)\right] \quad (5.13)$$

where $Kn$ is the Knudsen number and equals to the ratio of mean free path of the fluid to particle radius.

In Eq. (5.12), $C_D$ is the drag coefficient and is given as (Hinds, 2012):

$$C_D = \frac{24}{\mathrm{Re}}(1 + 0.15\,\mathrm{Re}^{0.678}) \qquad \mathrm{Re} \le 1000 \quad (5.14)$$

where Re is the Reynolds number.

In addition, the hydrodynamic torque acting on a spherical particle attached to a surface can be expressed as:

$$M_h = \frac{2\pi\mu f_m d^2 u_M}{C_c} \quad (5.15)$$

where $f_m$ is the wall effect correction factor and equals to 0.943993 (O'neill, 1968).

The equation for the instantaneous axial velocity in the viscous sublayer turbulence burst/inrush flows is given as:

$$u^+ = \Gamma y^+ \quad (5.16)$$

where $u^+$ is the flow streamwise velocity, $y^+$ is the distance to the wall, and $\Gamma$ is the coefficient to express the wall condition. For standard linear velocity variation, $\Gamma$ =1. However, for the turbulent flow with burst/inrush, $\Gamma$ =1.84 (Soltani & Ahmadi, 1995a).

Then, the fluid velocity for the particle center, $u_M$ as the function of shear velocity, $u^*$ which represents the friction stress magnitude of the air flow on the surface can be expressed as:

$$u_M = \frac{\Gamma d u^{*2}}{2\upsilon} \tag{5.17}$$

where $\upsilon$ is the fluid kinematic viscosity.

The particle Reynolds number, $\mathrm{Re}$ , can be expressed as the function of shear velocity as:

$$\mathrm{Re} = \frac{\Gamma d^2 u^{*2}}{2\upsilon} \tag{5.18}$$

Then, the hydrodynamic force and torque based on Eq. (5.12) and (5.15) can be expressed as the function as shear velocity as follows:

$$F_h = \frac{3\Gamma \pi f \rho d^2 u^{*2}}{2C_c}[1+0.15*(\frac{\Gamma d^2 u^{*2}}{2\upsilon})^{0.678}] \tag{5.19}$$

$$M_h = \frac{\Gamma \pi \mu f_m d^3 u^{*2}}{C_c} \tag{5.20}$$

Based on the values of adhesion force and hydrodynamic force and torque from Eq. (5.19) and (5.20), the minimum shear velocity for resuspension, $u^*$ , can be obtained from Eq. (5.1).

In this study, resuspension of dust particles ranging from 0.1 μm to 100 μm is analysed to compare the difference of cleaning effect by wind regarding different particle sizes.

### 5.2.3 Required shear velocity and wind velocity

After obtaining the shear velocity $u^*$ from Eq. (5.1), the next step is calculate the actual wind velocity for particle resuspension based on known shear velocity $u^*$. Shear velocity, $u^*$, is defined as:

$$u^* = \sqrt{\frac{\tau_w}{\rho}} \tag{5.21}$$

where $\tau_w$ is the wall shear stress and $\rho$ is the fluid density.

The wall shear stress, $\tau_w$, can be expressed as a function of skin friction coefficient, $C_f$. That is,

$$\tau_w = 0.5 C_f \rho U_\infty^2 \tag{5.22}$$

where $U_\infty$ is the actual wind velocity.

The skin friction coefficient is given as:

$$C_f = 0.0592 \,\mathrm{Re}_x^{-1/5} \tag{5.23}$$

where $\mathrm{Re}_x = U_\infty x/\nu$ is the Reynolds number.

So, the equation for actual wind velocity as the function of shear velocity for detaching deposited particle is given as from Eq. (5.21) to Eq. (5.23):

$$U_\infty = \sqrt{\frac{u^{*2}}{0.5 * 0.0592 * \mathrm{Re}_x^{-1/5}}} \tag{5.24}$$

## 5.3 Results

In this section, the shear velocity and actual wind velocity for particle resuspension are firstly discussed. Additionally, compared with the size distribution of deposited particle on PV module surface, large particle can be easily detached from the deposited surface. Finally, the influence of non-dimensional parameter and particle compositions on required shear velocity are analysed. The details are discussed as below:

### 5.3.1 Shear velocity for particle resuspension

In this study, as the main compositions of dust accumulation on PV module surface is silicon dioxide (Mani & Pillai, 2010), the parameters used in the calculation process are the property of silicon dioxide and glass surface of PV modules, as shown in Table 5.1. As shown in Figure 5.2, the predicted minimum required shear velocity for silicon dioxide particles re-suspended from glass covers of PV modules which are evaluated according to Eq. (5.1), (5.11), (5.19) and (5.20) for particle resuspension process ranges from 0.23 m/s to 57.56 m/s for different particle diameters. Clearly, the removal shear velocity decreases with the increase of particle size. Taking the inrush turbulent as example, when particle diameters increase from 0.1 μm to 1 μm, the required shear velocity is greatly reduced by 85% from 57.56 m/s to 7.77 m/s. However, the reduction rate is lower for particles with diameters from 10 μm to 100 μm, slightly reduced in value from 1.53 m/s to 0.31 m/s. It means that compared with small particle, large particle tends to be easily detached from the deposited surface because of the low ratio of increased adhesion force to the increased hydrodynamic force and torque in turbulent flow. Apart from the ratio between the adhesion force and the hydrodynamic force, the influence of gravity on shear velocity can be negligible because gravity is less than 1% of the adhesion force (Goldasteh et al., 2013).

Table 5.1 Parameters used in this study.

| Parameters | | Unit |
|---|---|---|
| Particle diameter (d) | 0.1-100 | μm |
| Non-dimensional roughness ($\Delta_C$) | 0.8 | |
| Thermodynamic parameter ($W_a$) | 0.4 | $J/m^2$ |
| Young modulus ($E_1$-$E_2$) | 6.9-6.9 | $10^{10}$ $N/m^2$ |

| | |
|---|---|
| Poisson ratio ( $v_1$ - $v_2$ ) | 0.2-0.2 |

Additionally, it is obvious that the required shear velocity for inrush turbulent ( $\Gamma$ =1) is larger than that for burst turbulent flow ( $\Gamma$ =1.84) and increases by 35.7%, which is also presented in Figure 5.2. The difference can be negligible for large particles, but obvious for small particles due to the large value in shear velocity for removal for small particles which is smaller than 10 μm. The reason is that the hydrodynamic force and torque are increased when high turbulent flow affects surface based on Eq. (5.19) and (5.20). So, with the decreased ratio of adhesion mechanism to hydrodynamic mechanism due to the high turbulent means, the required shear velocity is reduced.

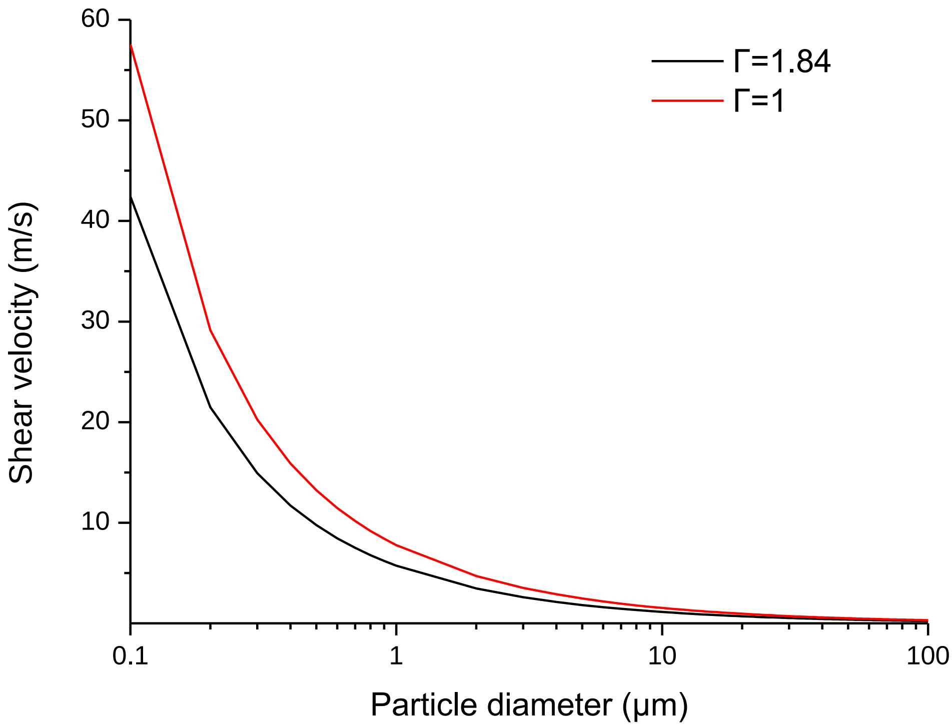



Figure 5.2 Shear velocity for particle resuspension.

### 5.3.2 Actual wind velocity for resuspension

Figure 5.3 presents the required actual wind velocity which is calculated from the known shear velocity based on Eq. (5.24) for silicon dioxide particles resuspension from glass surface of PV modules. The actual wind velocity varies from 0.82 m/s to 2219.8 m/s, and the ratio of shear velocity to wind velocity ranges from 0.04 to 0.06. Because the actual wind velocity is proportional to the square of required shear velocity as presented in Eq. (5.24), similar to Figure 5.2, the actual wind velocity increases with the decrease of particle diameter, and large particles can be effectively cleaned due to the smaller required wind velocity compared with small particles from Figure 5.3. For instance, actual wind velocity for removal with inrush turbulent is greatly decreased by nearly 98% from 2219.8 m/s to 39.5 m/s when particle diameter is lower than 1 μm. However, for large particles which are larger than 10 μm, the reduction rate of actual wind velocity is less because wind velocity for removal is approximately decreased by 83% from 39.49m/s to 6.77m/s. Moreover, the difference between burst and inrush flows reveals that the turbulent intensity of deposited surface can significantly affect the actual cleaning wind velocity, increasing 40.3% from burst turbulent flow to inrush turbulent state, which are also similar to the previous shear velocity results.

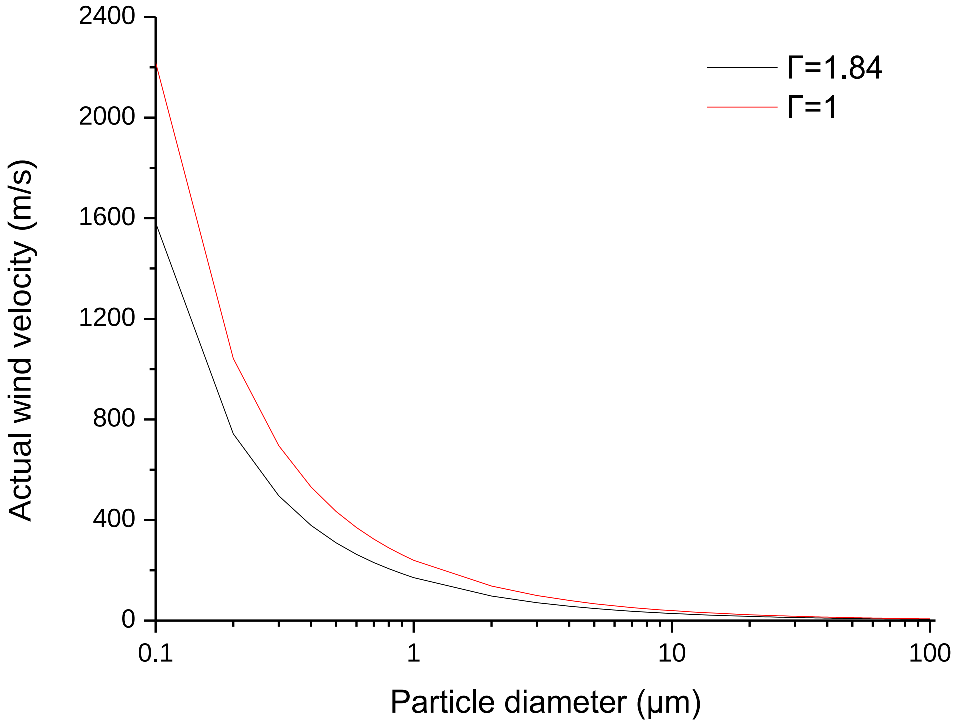



Figure 5.3 Actual wind velocity for particle resuspension.

### 5.3.3 Velocity verification with experimental deposited particle size distribution

As presented in Figure 5.4, the number of naturally deposited dust particles on PV modules on the roof of the University of Sonora was analyzed by a LS Particle Size Analyzer brand Coulter model Fraunhofer LS 100Q (Cabanillas & Munguía, 2011). Compared with Figure 5.2 and Figure 5.3, the number for particles with diameters larger than 0.6 μm is increased with the increase of particle diameter attributing to the low required velocity for resuspension. In addition, the number of large particles (diameter > 5 μm) is equal to zero, which strongly verified that large particles can be effectively removed by wind, as presented in Figure 5.2 and Figure 5.3.

However, owing to the number difference of particles with different diameters in the ambient air, the number of deposited particle distribution is decreased with the increase of particle diameter for small particles with diameter less than 0.5 μm. Apart from the quantity difference for small particle in atmosphere, small particles can aggregate into large particles on the PV module cover, and thus increase the number of large particles because the required wind velocity for these new aggregated particles with diameter less than 0.5 μm is not sufficiently small for resuspension as large particle with diameter higher than 1 μm. So, the distribution line agrees well with shear velocity and actual wind velocity results for large particles and verify the accuracy of this method based on particle resuspension model for evaluating the distribution of dust particles for actual PV modules.

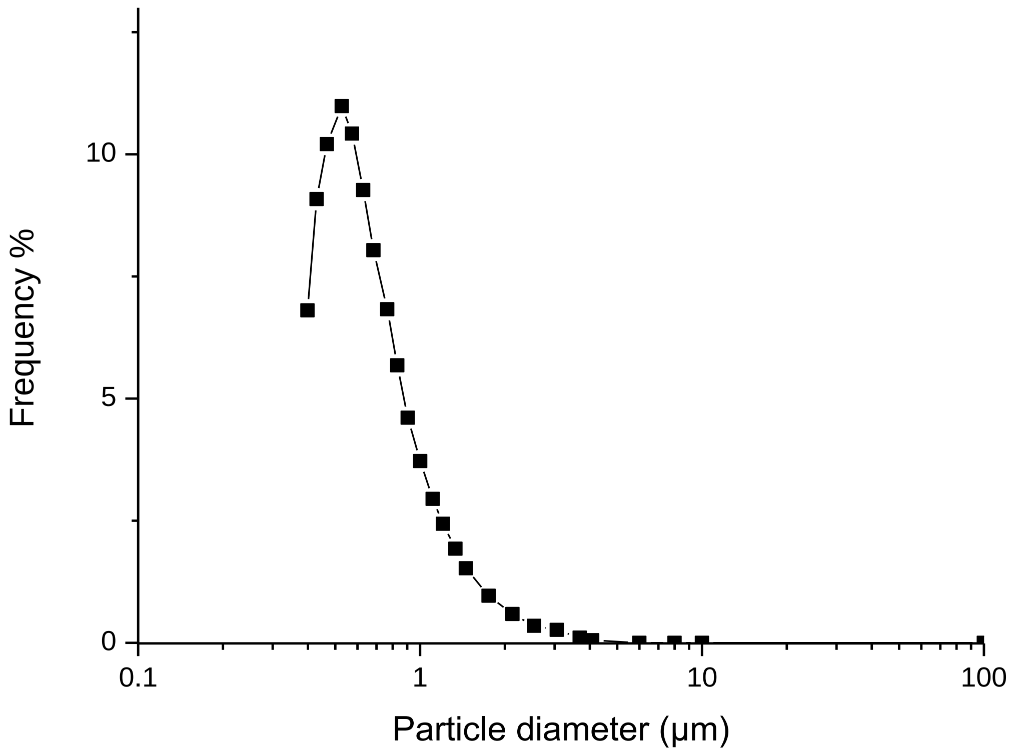



Figure 5.4 Number of particle distribution.

### 5.3.4 Effect of non-dimensional roughness parameter

The non-dimensional roughness parameter $\Delta_C$, a significant parameter in Eq. (5.6) to calculate the pull off force of particles due to the rough surface, highly depends on surface character and roughness level, and doesn't rely on particle size, generally assuming to range from 0.5 to 0.95 (Soltani & Ahmadi, 1999). Figure 5.5 shows the removal shear velocity of silicon dioxide particles from glass surface for different non-dimensional roughness parameters from 0.7 to 0.9 based on Eq. (5.1) and (5.11) to investigate the influence of non-dimensional roughness parameter on particle removal process. It can be obviously found that the required shear velocity is increased with the decrease of non-dimensional roughness parameter because the square of non-dimensional roughness parameter is proportional to the roughness height of surface, which means that rougher surface has smaller values in non-dimensional roughness parameter (Goldasteh, Ahmadi, & Ferro, 2012). When non-dimensional roughness parameter increases by 0.1, the shear velocity decreases approximately 20% because the non-dimensional roughness parameter dramatically increases the adhesion force and contact area as previously discussed in Eq. (5.6). Similar to the previous results, the differences between the selected non-dimensional roughness parameters are clearer for small particles and not obvious for large particles because small particles are easily affected by the roughness structure of deposited surface, such as strongly adsorbed in the gap of rough surface. Consequently, the recommended $\Delta_C$ used in the following study is 0.8 for particles with all diameters.

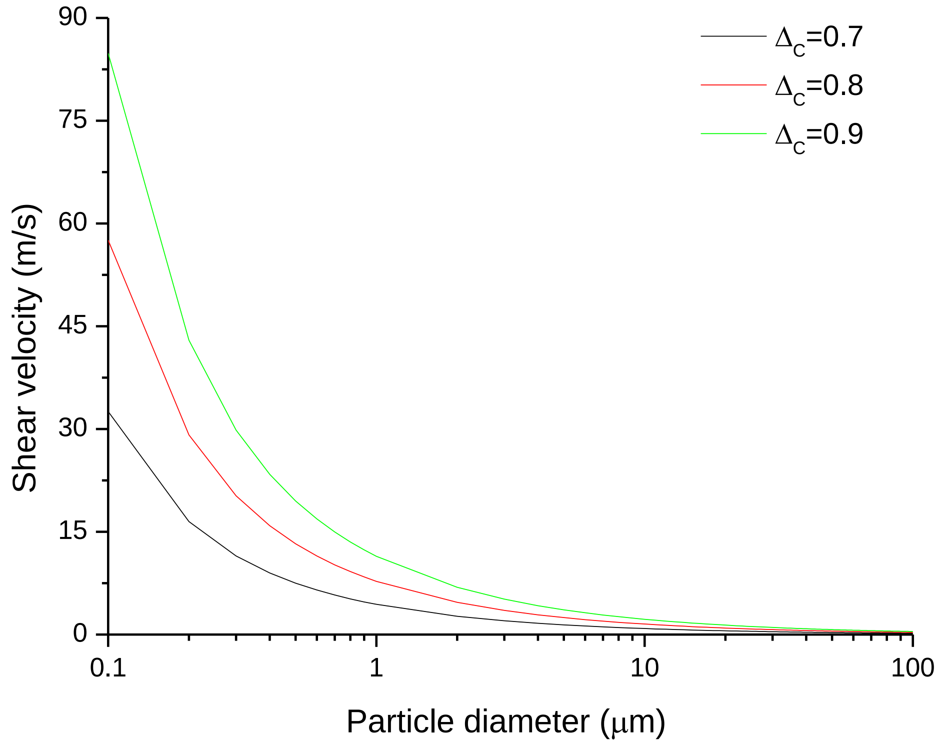



Figure 5.5 Shear velocity for different non-dimensional roughness parameter.

### 5.3.5 Effect of dust particle compositions

As presented in Table 5.2, the compositions of deposited dust on PV modules in four sites of Oman were analysed (Darwish et al., 2015b). Due to the high percentage (larger than 1%) in mass of the collected dust in four different sites, $MgO$, $Al_2O_3$, $SiO_2$, $CaO$ and $Fe_2O_3$ were chosen to be the representative particle compositions for this study. In the calculation process, other parameters to calculate the pull-off force for five kinds of representative compositions above, such as $W_a$ , $K$ and $\rho$ were also properly collected (Goldasteh et al., 2013).

Table 5.2 Deposited dust compositions (Darwish et al., 2015b).

| Site 1 | Border of Oman (Salty water) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $MgO$ | $Al_2O_3$ | $SiO_2$ | $SiO_3$ | $K_2O$ | $CaO$ | $TiO_2$ | $Fe_2O_3$ |
| Mass% | 6.93 | 7.91 | 41.76 | 2.84 | 0.79 | 24.94 | 0.76 | 12.26 |
| Site 2 | Border of Oman (No salty water) | | | | | | | |
| | $MgO$ | $Al_2O_3$ | $SiO_2$ | $SiO_3$ | $K_2O$ | $CaO$ | $TiO_2$ | $Fe_2O_3$ |
| Mass% | 6.33 | 10.83 | 45.53 | 0.24 | 0.87 | 24.62 | 0.45 | 10.46 |
| Site 3 | Desert road | | | | | | | |
| | $MgO$ | $Al_2O_3$ | $SiO_2$ | $SiO_3$ | $K_2O$ | $CaO$ | $TiO_2$ | $Fe_2O_3$ |
| Mass% | 3.99 | 3.81 | 55.79 | 0.21 | 1.16 | 30.40 | 0.31 | 3.94 |
| Site 4 | Fujairah city | | | | | | | |
| | $MgO$ | $Al_2O_3$ | $SiO_2$ | $SiO_3$ | $K_2O$ | $CaO$ | $TiO_2$ | $Fe_2O_3$ |
| Mass% | 17.37 | 3.42 | 38.11 | 0.56 | 0.06 | 21.02 | 0.35 | 16.68 |

As illustrated in Figure 5.6, the required shear velocity for five kinds of compositions varies from 0.31 to 89.0 m/s. The difficulty for resuspension for these is given as follows from Figure 5.6: $Fe_2O_3$ > $Al_2O_3$ > $MgO$ > $CaO$ > $SiO_2$. $Fe_2O_3$ has the highest difficulty for resuspension, because $Fe_2O_3$ has the largest adhesion force and contact area among all the high compositions of deposited dust from the calculation of Eq. (5.10) and (5.11) with the same size.

In addition to the direct outcome for resuspension difficulty of all compositions, the differences are not significant for most particle sizes but significant for small particles. So, due to the maximum in the mass and the insignificant differences in shear velocity for particle resuspension of various compositions, $SiO_2$ can be considered as the representative composition of dust particles for estimating the cleaning effect of wind on accumulated particles on PV modules in the resuspension calculation process, especially more applicable for dust particles with large diameters.

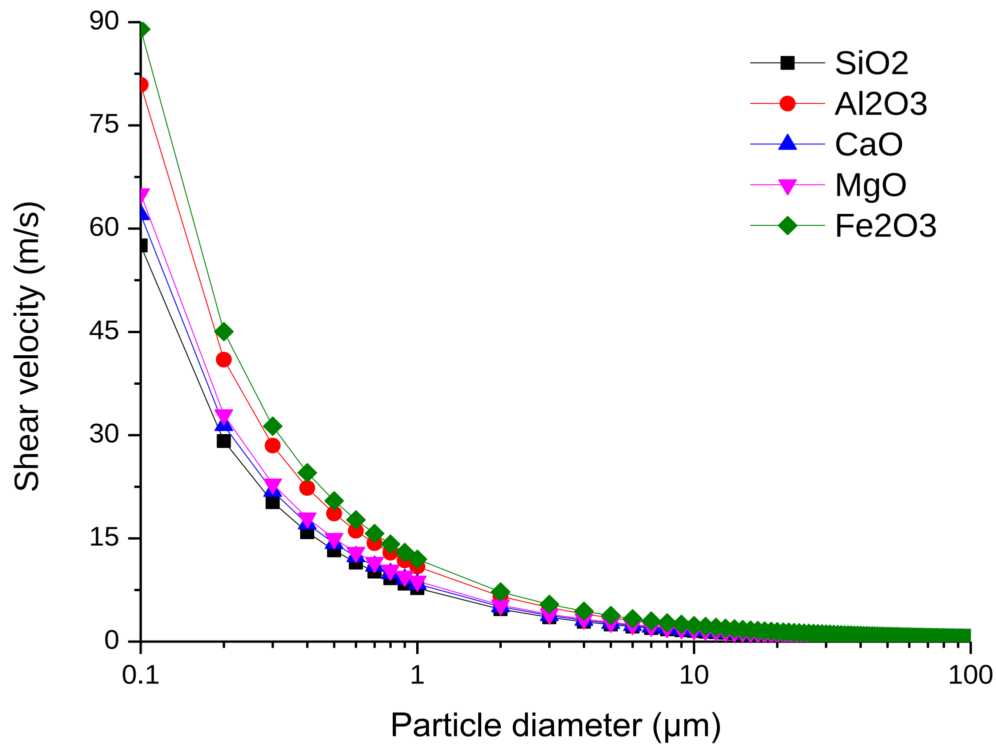



Figure 5.6 Shear velocity for different compositions.

### 5.3.6 Limitations of this method

The resuspension method developed in this study is mainly suitable for the detachment of spherical and rough particles from flat surface. It is obvious that the installed PV modules have optimal tilt angles and directions in order to receive solar radiation as much as possible for actual application based on the installed location. Therefore, for predicting the wind cleaning process for PV modules with inclined angles, the direction and velocity of airflow should be changed into actual velocity along the direction of PV modules. However, the relationship between the freestream velocity and the actual velocity on inclined flat is unclear. So, this method can be used for flat surface, and the influence of inclined angles on wind cleaning need further study. In addition, as stated before, this particle resuspension model is for spherical particles without considering the influence of particle irregularity. Thus, to obtain more accurate shear velocity for actual particles, the shape of actual particles should be measured and converted into spherical diameter for calculation process.

## 5.4 Summary

In this chapter, a resuspension model for rough and spherical particles detaching flat surface was firstly developed to analyze the cleaning effect of wind on the accumulated dust particles on solar PV modules. This model considers the adhesion force, hydrodynamic force and torque in turbulent flow. The minimum shear velocity and corresponding actual wind velocity for particle removal were calculated for particles with diameters ranging from 0.1 μm to 100 μm based on the correlation of adhesion force, hydrodynamic force and torque. It was found that large particles could be effectively cleaned by wind due to the low required resuspension velocity compared with small particles. Other findings are summarized as follows:

1) The minimum required shear velocity for dust particles (silicon dioxide particles) resuspension from glass surface of PV modules was found to range from 0.23 m/s to 57.56 m/s for different particle sizes between 0.1 μm to 100 μm, and decreased with the increase of particle diameter. For large particles, the decreasing rate of shear velocity is lower than that of small particles. Taking the inrush turbulent as example, the required shear velocity is greatly reduced from 57.56 m/s to 7.77 m/s for particle diameters from 0.1 μm to 1 μm and gradually decreased from 1.53 m/s to 0.31 m/s for particle diameters from 10 μm to 100 μm.

2) The actual wind velocity for silicon dioxide particles re-suspension from PV

module glass surface varied from 0.82 m/s to 2219.8 m/s, and the ratio of shear velocity to wind velocity ranged from 0.04 to 0.06. Similar to the results of shear velocity, actual wind velocity for removal with inrush turbulent is greatly decreased by nearly 98% from 2219.8 m/s to 39.5 m/s when particle diameter is lower than 1 μm and gradually decreased by 83% from 39.49m/s to 6.77m/s for large particles which are larger than 10 μm.

3) The shear velocity is increased with the decrease of non-dimensional roughness parameter because large non-dimensional roughness parameter means the high pull off force from deposited surface to dust particles. When non-dimensional roughness parameter increases by 0.1, the shear velocity decreases approximately 20% in this study and the recommended value for this parameter is 0.8.

The difficulty of main compositions of particles for removal were compared, shown as $Fe_2O_3 > Al_2O_3 > MgO > CaO > SiO_2$. $SiO_2$ is recommended to be the representative composition of dust particles for other theoretical study because of its negligible distinction in shear velocity for various compositions and the largest density, especially for large particles.

Therefore, these findings can verify that particle resuspension method is a significant way to analyse the wind cleaning process on deposited particles. In addition, considering the cleaning process of wind, more accurate model to estimate energy output for PV modules due to the accumulated dust can be developed for solar energy industry. Except for the wind cleaning process, as introduced in Chapter 2, the reasonable cleaning frequency for dust accumulation on PV modules is seldom investigated. Therefore, a theoretical method for calculating cleaning frequency for dust accumulation in desert environment will be presented in the next chapter.

# CHAPTER 6
# DEVELOPING A NOVEL MODEL TO ESTIMATE THE CLEANING FREQUENCY FOR DIRTY SOLAR PHOTOVOLTAIC (PV) MODULES IN DESERT ENVIRONMENT

## 6.1 Introduction

After presenting the particle resuspension model to evaluating the wind cleaning process for dust accumulation on PV modules, as discussed in Chapter 2, previous studies have reported the methods for cleaning or preventing dust accumulation on PV modules to increase their energy output, but the significant issue for cleaning PV modules with dust particles, the cleaning frequency, especially for desert areas, is seldom reported.

Therefore, the aim of this chapter is to propose a novel method to calculate the accumulated velocity of dust on PV modules and to estimate the module cleaning frequency for the desert environment. This method may help the engineers to predict the velocity of dust accumulation based on two or three parameters and to determine the frequency for preparing the cleaning equipment for the dirty PV modules. Therefore, it can make the operation of PV modules more efficient, avoiding the meaningless waste of cleaning water and manpower to reduce the maintenance cost.

## 6.2 Research method

### 6.2.1 Particle deposition velocity model

In general, commercial PV modules are composed of three parts, i.e. glass top covers for protection of core solar cell, crystalline silicon solar cells for generation of electricity by absorbing solar radiation and other electronic accessories for transportation of converted electricity. Airborne dust particles can deposited on the top glass covers, and the energy conversion performance of PV modules will be decreased because of the transmittance reduction of glass covers and less received solar irradiance accordingly. The relationship between the deposited dust density and PV module output power performance was experimentally investigated by our research group (H. Jiang et al., 2011). Therefore, this work focused on developing the theoretical model to estimate the cleaning frequency based on the particle deposition velocity model and the relationship between dust density and PV performance. In addition to crystalline silicon solar cells, other innovative materials, such as thin-film amorphous silicon solar cells, organic solar cells and perovskite solar cells, have attracted much attention due to their potential of higher conversion efficiency and lower costs. The accumulated dust particles on solar cells would block and absorb solar incident but would not significantly change the spectrum distribution of solar incident, as shown in Figure 6.1. Therefore, the model developed in this study can be applied not only for crystalline silicon solar cells but also for other kinds of solar cells.

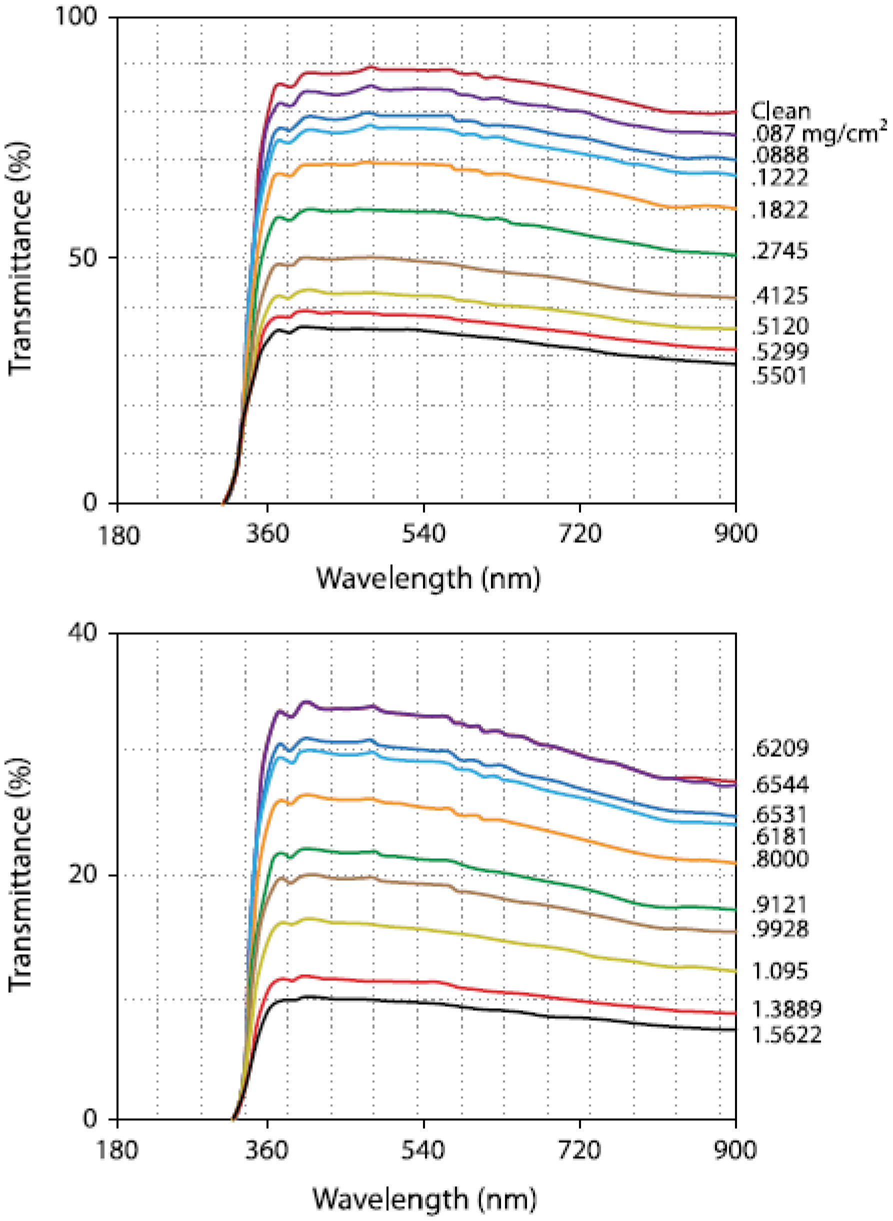



Figure 6.1 Spectral transmittance of light for glass samples with various dust accumulation densities(Al-Hasan, 1998).

In this work, the airborne dust was assumed as spherical particle. The theoretical model to estimate spherical particle deposition velocity onto inclined surfaces was based on the three layer model (You et al., 2012). The deposition particle flux in the model can be described as follows (Zhao & Wu, 2006a):

$$J = -(\varepsilon_p + D)\frac{\partial C}{\partial y} - i\upsilon_s C + V_t C \qquad (6.1)$$

where $\varepsilon_p$ is the particle eddy diffusivity in the boundary near the surface, $D$ is the particle Brownian diffusivity, $\upsilon_s$ is the settling velocity due to gravity (m/s), $i$ is the parameter for surface orientation, $V_t$ is the turbophoretic velocity (m/s), $C$ is the particle concentration ($kg/m^3$) and $y$ is the distance between particles and the surface (m). By considering the effect of the Brownian diffusion, the turbulent diffusion, the gravitational settling and the turbophoresis on particle deposition process, this model can accurately estimate the particle deposition velocity on a plate surface.

The theoretical model used in this study includes four parts in term of particle diameter, i.e. “Fine zone”, “Coarse zone”, “Zero zone”, and “Transition zone”, respectively. The equation for each zone consists of two parts: the equation itself and the corresponding applied range. In the “Fine zone”, where particles have small diameters, the inclined angles have no effect on particle deposition velocity. The “Coarse zone” is for particles with large diameters and for surfaces with the inclination angle smaller than 90◦. In this zone, particle deposition velocities are proportional with the cosine function of the inclination angle of the surface. The “Zero zone” is for surfaces with the inclination angle larger than $90^o$, so it is not used in this study because the angle of installed PV panels is less than $90^o$. The ‘Transition zone’ is for the remaining data. The errors for these four parts are 1.53%, 1.50%, within 10% and 21.93%. So, this empirical model can be used in the calculation process for particle deposition velocity on PV modules, although the error is relatively large in the transition zone because this zone has no certain regulation and is insignificant in the actual calculation process.

The first parameter which needs to be estimated in the theoretical model is the friction velocity $u^*$. Friction velocity represents the friction stress magnitude of the air flow on the surface and the general expressions for deposition velocity are the function of surface friction velocity. The formula is given as below:

$$u^* = \sqrt{\frac{\tau_w}{\rho}} \tag{6.2}$$

where $\tau_w$ means the wall shear stress and $\rho$ is the fluid density(kg/m$^3$).

Wall shear stress, $\tau_w$, can be estimated by:

$$\tau_w = \frac{1}{2} C_f \rho U_\infty^2 \tag{6.3}$$

where $C_f$ is the skin friction parameter and $U_\infty$ is the free stream velocity (m/s) and equals to the local wind velocity.

The skin friction parameter can be estimated by (Schlichting, 1979):

$$C_f = 0.0592 \mathrm{Re}_x^{-1/5} \tag{6.4}$$

where $\mathrm{Re}_x$ is the Reynolds number of the local air.

Then, the particle deposition velocity for particle with one specific diameter can be estimated by the following equations based on the calculated friction velocity from Eq. (6.2) to Eq. (6.4) (You et al., 2012):

$$v_{di} = \begin{cases} (5.15\times10^{-8}u^* - 5.63\times10^{-11})d_p^{-1.263} & d_p < 0.0512(u^*)^{0.4227} \\ 3.7\times10^{-5} d_p^{1.9143}(\cos\theta) & d_p > 0.3577(\cos\theta)^{-0.41}, \cos\theta > 0 \\ 0 & d_p > g(u^*, \cos\theta), \cos\theta \le 0 \\ f(u^*, \cos\theta, d_p) & \text{for others} \end{cases} \tag{6.5}$$

where $d_p$ is the particle diameter (μm), $\theta$ is the installed inclined angle of PV modules.

Because the tilt angle of installed PV modules is generally less than 90 degrees, the third term of this equation for particles belonging to the zero zone, can be negligible in this study.

### 6.2.2 Cleaning frequency calculation for PV modules

Generally, mechanical cleaning and preventative coating are two main methods to mitigate the dust pollution on solar PV modules. The most common mechanical cleaning is to wash away the accumulated dusts from the PV module surfaces by water. The other way for reducing dust pollution is to cover super-hydrophilic self-cleaning coating on PV module surface, and then the dusts on the PV modules would be easily cleaned by rainwater due to the hydrophilic property of modified surface. However, this coating way is not suitable for desert region where the rainfall is quite rare. Besides, air flow and vibration are also accessible approaches for cleaning the dirty PV surface (Sarver et al., 2013). For solar PV power plants located in the desert, washing by water cannon is the most usual way for effectively cleaning dirty PV modules and maintaining the high energy conversion output. However, it's always challenging to determine the cleaning frequency in different regions, as the dust properties, size distribution and wind conditions are quite different. Therefore, this study tried to develop a simplified model to estimate the cleaning frequency for engineering application.

Based on the obtained particle deposition velocity from Eq. (6.5), the cleaning time then can be estimated by:

$$T = M_d \times A \div (A \times C_d \times V_d) = \frac{M_d}{C_d \times V_d} \tag{6.6}$$

where $M_d$ is the particle accumulation density for a specific power loss (kg/m$^3$); A is the area for PV modules (m$^2$); $V_d$ is the particle deposition velocity obtained from formula 6.5 with a representative average diameter (m/s); and, $C_d$ is the particle mass concentration in the ambient air (kg/m$^3$).

To estimate the cleaning frequency in a specific region, the cleaning criterion, which means the power output reduction value by accumulated dust, is the significant parameter. It was pointed out that the cleaning process is necessary if the reduction of PV module output power performance is higher than 5%. Therefore, the cleaning criterion used in this study was the 5% decrease in power output due to the accumulated dust. Output reduction is strongly dependent on the density of accumulated dust and several models have been built to show the relationship (Al-Hasan, 1998; Ju & Fu, 2011). Based on the experimental results conducted by our research group, the accumulated dust density is 2 g/m$^2$ when the energy output power reduction equals to 5% for common PV modules with different silicon solar cells, as presented in Figure 6.2. Thus, it indicates that the PV modules need to be cleaned when the deposited dust density equals to 2 g/m$^2$ in the theoretical model of this study.

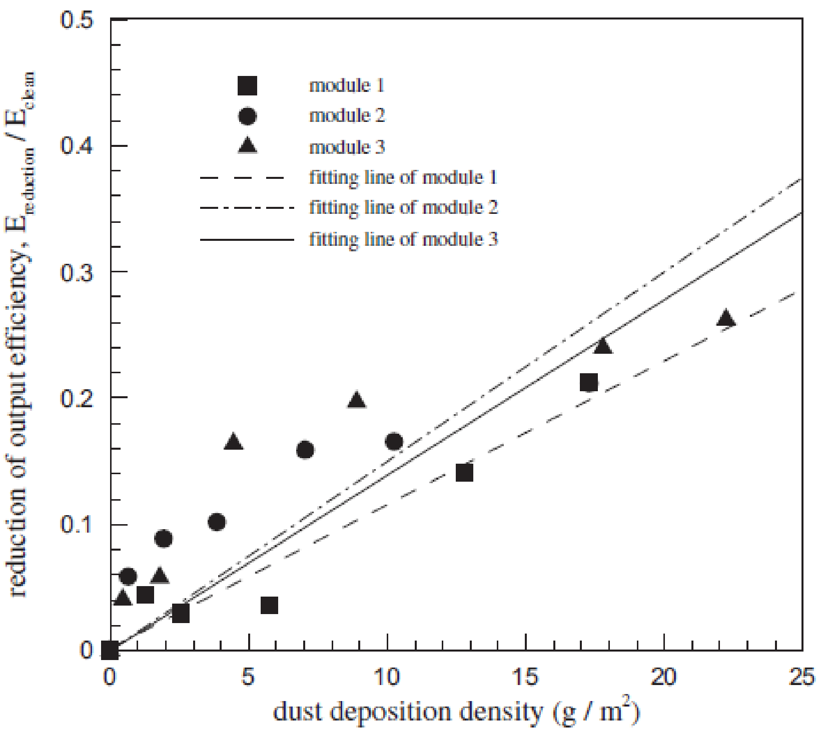



Figure 6.2 Output efficiency reductions with different dust deposition density for three kinds of silicon solar PV modules (H. Jiang et al., 2011).

### 6.2.3 Data collections of influencing parameters

To apply the previously mentioned speedy calculation method for estimating the dust deposition velocity on PV modules and corresponding cleaning frequency, several parameters need to be correctly obtained, including the PV module installation angle, representative average diameter of the accumulated dust and the dust mass concentration in the local atmosphere.

Generally, the optimal inclined angle of PV modules for receiving most solar irradiance is highly dependent on the installation global location. Theoretically, the best tilt angle is different with various sun positions and seasons. However, for large-scale PV stations, adjusting the inclined angle according to the seasonal changes is uneconomic. Thus, a representative tilt angle was chosen in engineering application that this tilt angle can show the best performance of PV modules all the year around. The best installation angle of PV modules is roughly equal to local altitude (L. Lu, Yang, & Burnett, 2002). Therefore, to examine the influence of various tilt angles on the dust deposition velocity, six different inclined angles ($0^o$, $15^o$, $30^o$, $45^o$, $60^o$, $75^o$) were chosen in this study to compare the effect of different tilt angles. In this study, since most desert regions locate in low or med-latitudes, the four different inclined angles were selected ($0^o$, $15^o$, $30^o$, $45^o$).

According to the experimental study in Mexico, the diameter of accumulated dust on PV module ranges between 0.4 and 400 µm, and particles with a diameter of about 20 µm are the most representative and occupy the largest number percentage (Cabanillas & Munguía, 2011). Therefore, 20 µm was chosen as the average diameter of dust used in this study. For actual dust particles, the sizes are various for different zones. So, one accurate way for engineers to obtain the local representative diameter of accumulated dust is measuring the size distribution of dust samples and calculating the average particle diameter based on Eq. (6.5). However, to simplify the difficulty of obtaining representative diameter, the experimental data by Cabanillas and

Munguis were chosen as above.

For dust mass concentration, as mentioned that the average diameter is higher than 2.5 μm, $PM_{10}$ data are proper for the particle concentration, and the average $PM_{10}$ concentration of most areas is lower than 100 μg/m$^3$ based on the ambient (outdoor) air pollution in cities database 2015 from World Health Organization. Thus, 100 μg/m$^3$ of $C_d$ was used in this study.

## 6.3 Results and discussions

This section can be divided into three parts. The first part is the calculated cleaning time of different inclined angles of this study. Then, the calculated cleaning time is compared with previous measured findings to validate the reliability of calculated results. Finally, the impact of dust accumulation density, average particle diameter, inclined tilt angles and wind velocity on cleaning frequency are discussed respectively. Details are presented as below:

### 6.3.1 Module cleaning frequency for desert environment

As discussed above, in this study, the environmental parameters were 20 μm for representative average diameter, four different tilt angles (from 0 to 45°) and 100 μg/m$^3$ for particle concentration in the ambient air respectively. In addition, the cleaning criterion was 5% reduction in power output, and thus the accumulated dust density was 2 g/m$^2$. For the deposited dust particles on the surface of PV modules, the main composition is silicon dioxide (Darwish et al., 2015b). Thus, the type of dust used in this method is spherical silicon dioxide particle because this kind of particle can well model the actual deposition process of airborne dust particles in desert areas. Based on Eq. (6.2) to Eq. (6.6), the calculated cleaning times for PV modules in desert regions are from 20.7 days to 29.27 days, and slightly increased from horizontal position to inclined angle of 45°, as presented in Figure 6.3. It means that in desert areas, the recommended cleaning frequency is approximately once in three weeks or one month for engineers in order to maintain the high power output and energy generation performance of PV modules.

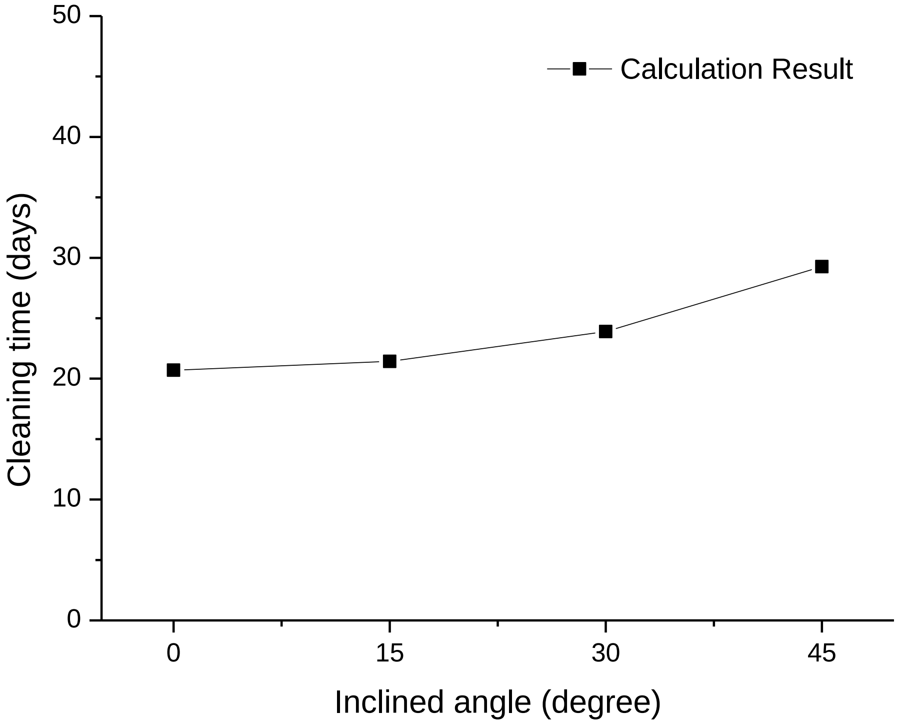



Figure 6.3 Calculated cleaning time for different inclined angles of this study.

### 6.3.2 Verifying the calculated cleaning time with previous research findings

To effectively compare the calculated results with other field studies, a parameter of average daily loss of PV module output power is defined as follows:

$$P_{DL}=P_{TL}/T_{EP} \tag{6.7}$$

where $P_{DL}$ means the average daily power loss (%/days), $P_{TL}$ means the total power loss in other field studies for PV modules in desert areas without cleaning process (%), and $T_{EP}$ means the total experimental time (days). $P_{DL}$ is a calculated parameter to measure the average output power reduction velocity, even though the actual daily loss is not fixed.

Table 6.1 shows the details of average daily loss from other outdoor research experimental findings in desert environments. The calculated average daily loss of this study is 0.25% and most of the daily loss for other field studies approximately are equal to the calculated result in value, ranging from 0.09% to 0.72%, as presented in Figure 6.4. It can be found that the present calculated daily loss is in good agreement with the related literature results. Therefore, the calculated result is credible and this verified method can be applied for the PV module cleaning in actual desert areas.

Table 6.1 Field studies in various desert areas.

| **Reference** | $T_{EP}$ | $P_{TL}$ | $P_{DL}$ |
|---|---|---|---|
| This study | 20.7 days | 5% | 0.24% |
| Nimmo and Said (Nimmo & Said, 1981) | 2 months | 15% | 0.25% |
| Al-Busairi and Al-Kandari (Al-Busairi & Al-Kandari, 1987) | 14 months | 55% | 0.13% |
| Salim et al. (Salim et al., 1988) | 12 months | 32% | 0.09% |
| Cabanillas and Munguia (Cabanillas & Munguía, 2011) | 20 days | 5%-14% | 0.25%-0.7% |
| Hanai et al. (Al Hanai, Hashim, El Chaar, & Lamont, 2011) | 18 days | 13% | 0.72% |
| Rehman and El-Amin (Rehman & El-Amin, | 1 month | 5.9% | 0.20% |

| | | | |
|---|---|---|---|
| 2012) | | | |
| Adinoyi and Said (Adinoyi & Said, 2013) | 8 months | 45.4%-49% | 0.19%-0.20% |

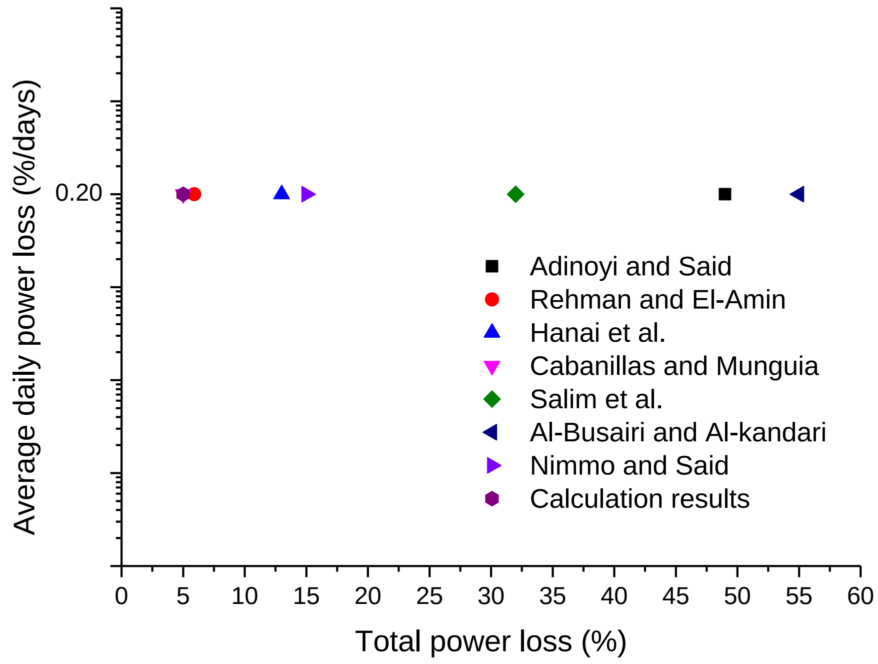



Figure 6.4 Average daily power loss of calculated results and other field studies.

### 6.3.1 Influence of accumulation dust density

Figure 6.5 shows the calculated cleaning time for different particle accumulation densities. It is obvious that the cleaning time is increased with the increase of accumulation density. For example, when the accumulation density is increased from 1 g/m$^2$ to 10 g/m$^2$, the cleaning time is decreased from 31281 days to 101 days for accumulated particles with the average diameter of 10 μm.

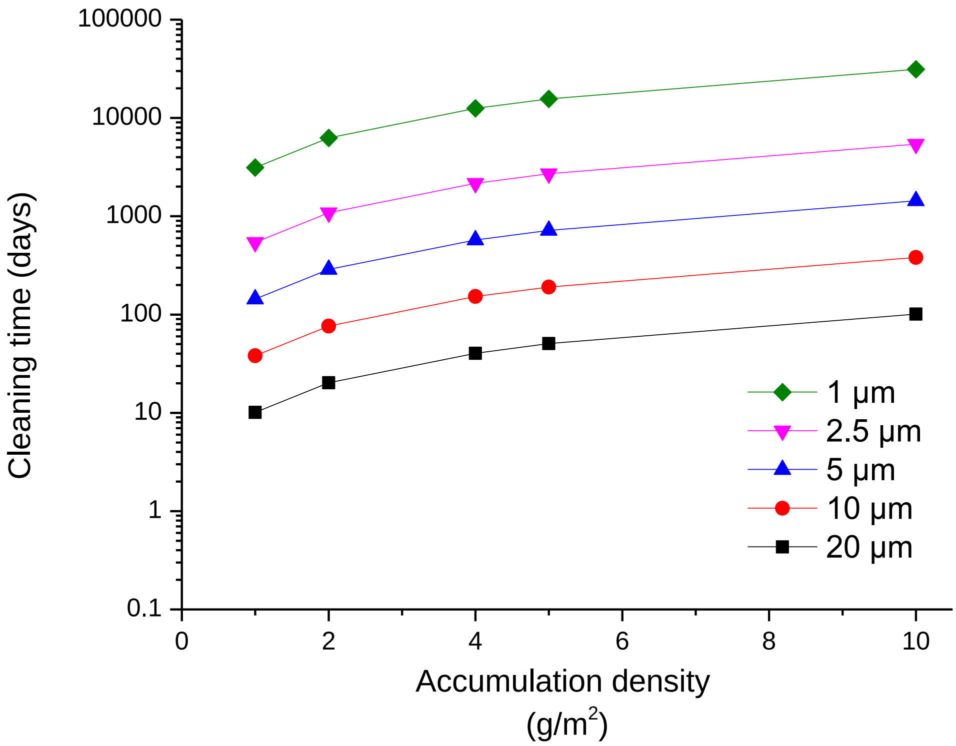



Figure 6.5 Cleaning time for various accumulation densities.

Accumulation density can be greatly influenced by two parameters, i.e. the composition of dust particles and the average diameter of accumulated dusts. For the composition of dust particles, even though quartz is the majority of accumulated dust, the percentages of other compositions are greatly different in various locations (Darwish et al., 2015b; Elminir et al., 2006). Thus, the total ability of dust in refracting and absorbing solar irradiance should be changed due to the various percentages of dust compositions. For the other parameter of the average diameter of accumulated dust, in addition to the main influence of particle diameter on deposition velocity, its effect on accumulation density cannot be negligible. In fact, the particles with small diameter (0.6–2μm) have the most significant role in light scatting because the distribution is closer (Roth & Pettit, 1980). So, the actual accumulation density should be lower due to the higher light scatting ability for particles with diameter less than 20 μm in this study.

### 6.3.2 Influence of average particle diameter

Apart from the accumulation density, another notable parameter for calculating the cleaning time is the representative average particle diameter. As presented in Figure 6.6, the cleaning time decreases with the increase of particle diameter. For instance, the cleaning time decreases from 12512 days to 7 days when the particle diameter increases from 1 μm to 20 μm. As discussed above for the deposition model, the average diameter of accumulated dust belongs to the coarse zone. Particle deposition mainly attributes to gravity in this zone. Gravity would play a crucial role on dust deposition compared with the Brownian and turbulent diffusion, as gravity would be increased with the increase of dust diameter. Therefore, the particle deposition velocity increases and the corresponding cleaning time decreases. In addition, if particles are larger than 5 μm, the cleaning time is lower than 100 days and the cleaning process should be considered in engineering application. Otherwise, if particle diameter is smaller than 5 μm, the cleaning issue in not worth conducting often because the cleaning frequency is too long.

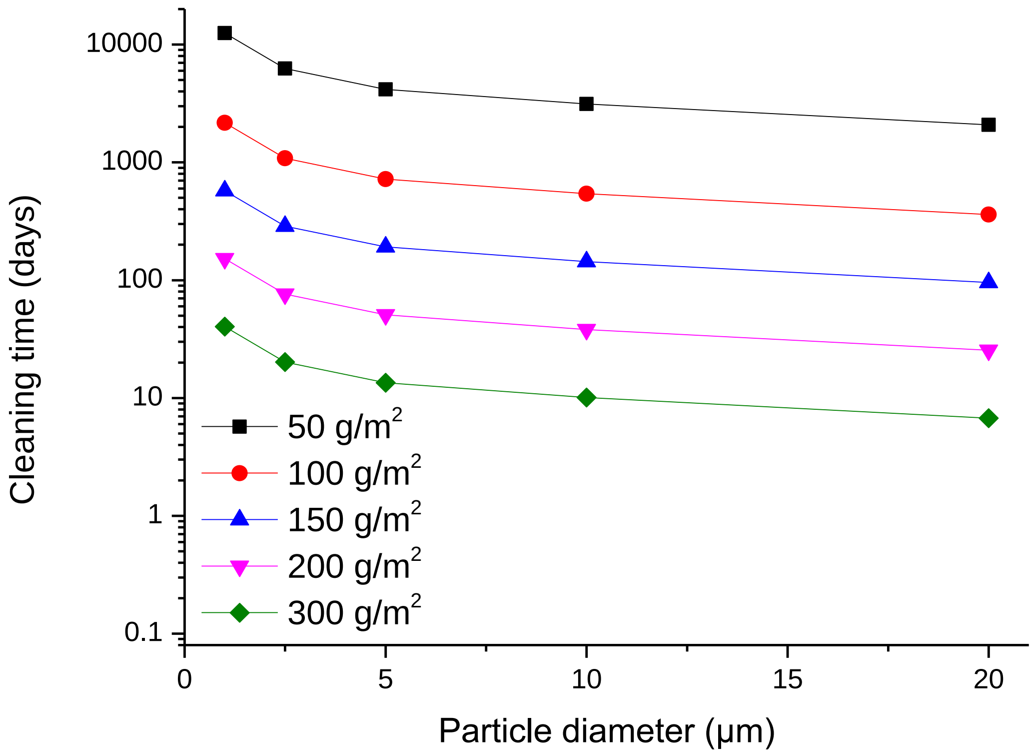



Figure 6.6 Cleaning time for different representative particle diameters.

### 6.3.3 Influence of installation tilt angles

Figure 6.7 presents the cleaning time results under six installation inclined angles (0, 15 º, 30 º, 45 º, 60 º, 75º). It can be observed that the cleaning time increases with the increase of tilt angle. As mentioned above, the average diameter of accumulated dust belongs to the coarse zone. In the coarse zone, particle deposition velocity is greatly influenced by gravity. In the meantime, higher tilt angle presents lower gravity due to the effect of tilt angle. In addition, the influence of friction velocity is negligible in this zone. This finding illustrates that high tilt angle can decrease the particle deposition density, which is in agreement with other reported results (Garg, 1974; Nahar & Gupta, 1990; Qasem et al., 2014). In general, the deserts are located in low or mid altitude where is lower than 50 degrees and the best inclined angle is equal to local altitude. So, cleaning process needs once a month when average particle diameter of deposited dust is larger than 10 μm.

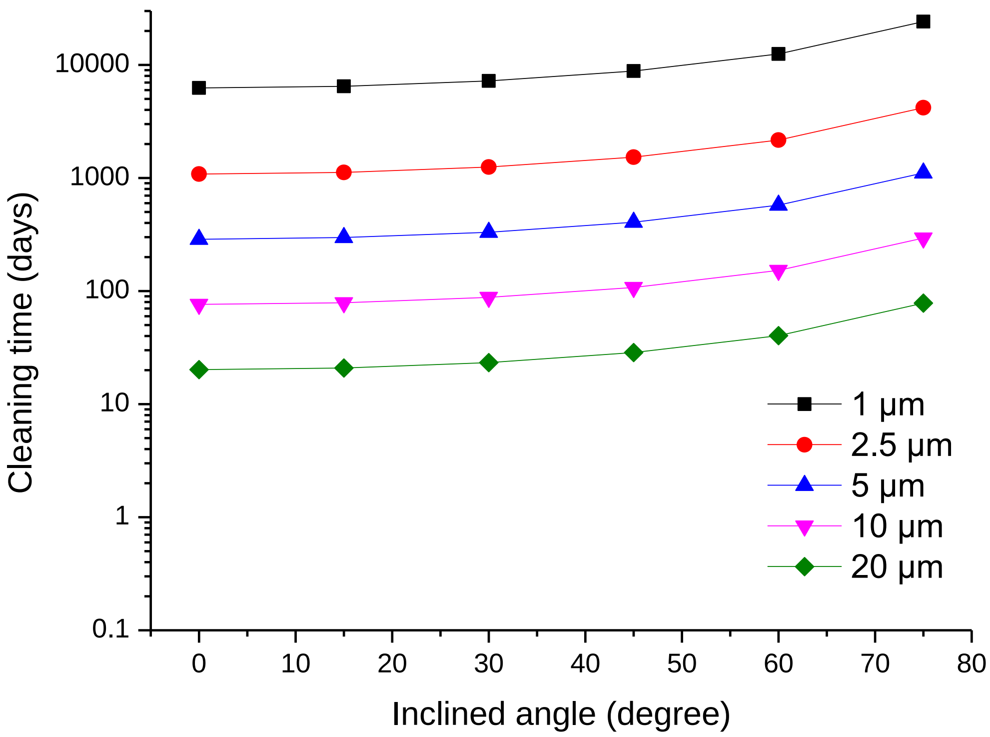



Figure 6.7 Cleaning time for different tilt angles.

### 6.3.4 Influence of wind velocities

Table 6.2 lists the results of cleaning time with various wind velocities for horizontal position. Obviously, the cleaning time is unchanged when the wind velocity increases from 1 to 10 m/s for large particles whose average diameter is larger than 1 μm, as shown in Figure 6.8. The first reason is that the deposition velocity of coarse particles is dominated by gravity and wind velocity affects little on the gravity. However, as presented in Chapter 5, wind plays significant role in cleaning dust particles and thus greatly affect the distribution of dust accumulation because large deposited particles can be easily resuspended from PV module covers by wind. In addition, even though higher wind velocity leads to higher turbulent diffusion due to the increase of turbulence and thus increase the deposition velocity, decreasing the cleaning time for particles belonging to fine zone, the deposition velocity of fine zone is too small compared with the particles of coarse zone and the recommended representative average size of particles for the calculation method belongs to coarse zone. Consequently, the impact of wind velocity for the cleaning time can be negligible in calculation process.

Table 6.2 Cleaning time (days) with different wind velocities.

| Wind Velocity (m/s) | 0.1 μm | 1 μm | 5 μm | 10 μm |
|---|---|---|---|---|
| 1 | $2.3\times10^{5}$ | 1082.9 | 287.3 | 76.2 |
| 2 | $1.1\times10^{5}$ | 1082.9 | 287.3 | 76.2 |
| 5 | $4.5\times10^{4}$ | 1082.9 | 287.3 | 76.2 |
| 8 | $2.8\times10^{4}$ | 1082.9 | 287.3 | 76.2 |
| 10 | $2.3\times10^{4}$ | 1082.9 | 287.3 | 76.2 |

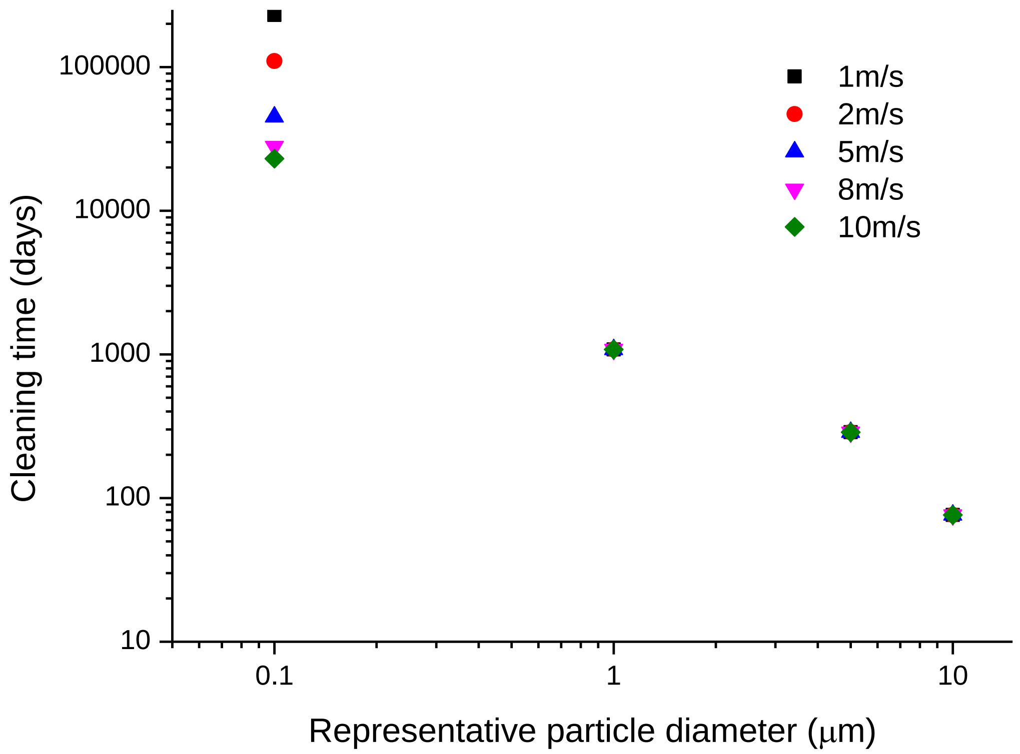



Figure 6.8 Cleaning time for different wind velocities.

### 6.3.5 Limitations

This novel method for cleaning time calculation is developed based on particle deposition velocity and accumulation density, but it ignores the cleaning process of rainfall which is the most efficient cleaning agent for removing dust particles. After the rainwater flows the dirty surface of PV modules, soluble composition of dust can be effectively detached from glass covers and the performance of PV modules would be thus increased (Appels et al., 2012; Haeberlin & Graf, 1998). Therefore, this method is more accurate for desert areas where precipitation is extremely scarce.

Apart from rainwater, wind can also naturally clean the dirty PV modules cover, detaching deposited particles from glass surface to the air flow and increasing the cleaning time (Goossens & Van Kerschaever, 1999). So, similar to the conclusion of rainfall, the calculated cleaning time is more precise for the zone with mild wind.

## 6.4 Summary

In this chapter, a novel method to estimate the cleaning frequency for dirty PV modules in desert areas has been establish based on the existing particle deposition velocity model. To calculate the cleaning frequency, average deposited dust particle diameter, inclined angle and particle concentration in the ambient air need to be obtained. The environmental parameters used in this study were 20 μm for representative average diameter, $0^o$ for tilt angle (horizontal position) and 100 μg/$m^3$ for particle concentration in the ambient air respectively. In addition, the cleaning criterion was 5% reduction in power with accumulated dust density of 2 g/$m^2$. The cleaning frequency for PV modules in desert regions is about 20 days. Therefore, it's recommended that the PV modules cleaning can be determined as three weeks to keep the high power output. In addition, some conclusions can be drawn as follows:

1) The calculated cleaning time based on the present method agrees well with the related experimental results by comparing the average daily power loss. Therefore, this verified method can be adopted in engineering application to estimate the cleaning frequency of dirty PV modules.

2) The average particle diameters and tilt angles can significantly influence the required cleaning time because the deposition velocity is highly dependent on gravity. The cleaning time was decreased to 20 days from 6256 days with the increase of representative average diameter from 1 μm to 20 μm and, was increased to 78.2 days from 20.2 days with the increase of the inclined angle from 0 degree to 75 degree because of the decrease in impact of gravity, respectively.

3) Wind velocity has little effects on the required cleaning time because the average diameter belongs to the coarse zone even though it can increase the deposition velocity of the particles in the fine zone. In this method, the impact of wind can be

ignored because recommended representative average particle diameter belongs to the coarse zone. However, wind can obviously affect the distribution of dust particles and the average particle diameter should be measured for practical application.

4) Considering the natural cleaning effects of rainfall and wind, this model is more accurate for desert environment where precipitation and wind resource are extremely scarce.

Therefore, based on the recommended cleaning frequency calculated in this study for desert environment, reasonable cleaning plan for eliminating dust accumulation can make the operation of PV modules more efficient, avoiding the meaningless waste of cleaning medium and manpower to reduce the maintenance cost.

Then, all of my work for this thesis has presented, including the influence of temperature differences and generated current on dust accumulation process on PV module surface, a method to evaluate the wind cleaning process for dust accumulation based particle resuspension model and a method to calculate cleaning frequency for desert environment. The next chapter is the summary chapter and the ideas for the future work from my research study.

# CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Dust accumulation can greatly decrease the energy conversion performance of PV modules. This thesis aims to study the influence of operational PV modules on dust accumulation process by particle deposition experiments, including temperature differences between glass covers with high temperature and the ambient air with low temperature and generated current due to the photovoltaic effect of solar cells. In addition, the method to evaluate wind cleaning effect on dust accumulation on PV modules is established and the method to calculate the reasonable cleaning frequency for desert areas is presented in this thesis. The main results of this thesis are summarized as below in this chapter.

## 7.1 Effect of temperature differences on dust accumulation process

The effect of temperature difference (thermophoresis) on dust accumulation process are experimentally investigated by particle deposition experiments in a test chamber, including glass samples and actual PV module samples. All findings are summarized as follows:

- The measured deposition densities of fine aerosols are from 0.05 to 0.19 $g/m^2$ under the experimental conditions for glass samples. The glass with higher surface temperature has lower density due to the effect of thermophoresis arising from temperature differences.
- Generally, the deposition densities decrease with the increase of sample tilt angles for all conditions due to the combination effect of aerosol gravity and aerosol surface adhesion.
- The glass light transmittance ratios increase with the increase in temperature

differences and tilt angles, ranging from 0.975 to 0.996.

- The experimental results agree well with the calculation results, so the equation of Tablot can be used to estimate the effect of temperature difference on dust accumulation process on PV modules.
- The measured deposition densities of fine particles ranged from 0.54 $g/m^2$ to 0.85 $g/m^2$ under the experimental conditions for PV module samples with different surface temperatures. The PV module with a higher surface temperature experienced a lower dust density due to the effect of thermophoresis arising from the temperature difference.
- The output power ratios increased from 0.861 to 0.965 with an increase in temperature difference from 0 to 50 °C. The results also show a similar dust deposition trend due to the thermophoresis force in the particle deposition process.
- Dust particles have a significant impact on the short circuit current and the output power. However, the influence of particle on the open circuit voltage can be negligible.

## 7.2 Influence of generated current and corresponding electrostatic force on dust accumulation process

The impact of generated current on dust accumulation process is also experimentally studied.

- The deposition density ranged from 0.17 $g/m^2$ to 0.41 $g/m^2$ for different module currents, and increased with the increase of provided currents. The reason for this is that dust particles result from the generated electric field due to the generated current.

- The particle deposition velocity depends on particle size and charge level, turbulent intensity, electric field strength and surface material. The Coulombic force plays an important role in particle deposition for the operating solar PV modules. For particles at extremely high charge level and in the presence of a strong electric field, the Coulombic force contributes significantly by enhancing deposition of accommodation mode particle size. The image force is important when the particle charge level is high and the electric field strength is weak.
- The calculated particle deposition velocity due to Columbic force under strong electric field based on Eq. (4.1) ranges from 7.34×10-7 m/s to 3.12×10-4 m/s for different particle diameters. When particle diameters increase from 0.01 μm to 0.5 μm, deposition velocity decreased nearly 75% from $3.12\times10^{-5}$ m/s to $7.34\times10^{-6}$ m/s because small particle is significantly influenced by Columbic force when compared with large particle in this size range. However, when particle diameters increase from 0.5 μm to 10 μm, the deposition velocity due to electric field is greatly increased 100% from $7.34\times10^{-6}$ m/s to $1.51\times10^{-5}$ m/s because large charging numbers for large particles.
- Deposition velocity of image force is increased with the increase of particle diameters because deposition velocity of image force is proportional to the particle charge level and large particle has large particle charging number based on diffusion charging mechanism. In addition, deposition velocity is also increase with the increase of dielectric constant.

## 7.3 Analyzing wind cleaning process on dust accumulation on solar photovoltaic (PV) modules

A resuspension model for rough and spherical particles detaching flat surface is firstly developed to analyse the cleaning effect of wind on the accumulated dust particles on solar PV modules. This model considers adhesion force, hydrodynamic force and torque. The minimum shear velocity and corresponding actual wind velocity for particle removal are calculated for particles with diameters ranging from 0.1 μm to 100 μm based on this model. It is found that large particles could be effectively cleaned by wind due to the low required resuspension velocity compared with small particles. Other findings are listed as follows:

- The minimum required shear velocity for particle resuspension process were found to range from 0.23 m/s to 57.56 m/s for different particle sizes, and increased with the increase of particle diameter.
- The actual wind velocity varied from 0.82 m/s to 2219.8 m/s, and the ratio of shear velocity to wind velocity ranged 0.04 to 0.06.
- The shear velocity is increased with the decrease of non-dimensional roughness parameter.
- Different compositions of particles were compared, and $SiO_2$ is chosen because of its negligible distinction in shear velocity for various compositions, especially for large particles.

Therefore, these findings can verified that particle resuspension method is a significant way to analyse the wind cleaning process on deposited particles. In addition, considering the cleaning process of wind, more accurate model to estimate energy output for PV modules due to the accumulated dust can be developed for solar energy industry.

## 7.4 Developing novel model to estimate the cleaning frequency for dirty solar photovoltaic (PV) modules in desert environment

A novel method to estimate the cleaning frequency for dirty PV modules in desert areas has been establish based on the existing particle deposition velocity model. The environmental parameters used are 20 μm for representative average diameter, $0^o$ for tilt angle (horizontal position) and 100 $\mu g/m^3$ for particle concentration in the ambient air respectively. In addition, the cleaning criterion is 5% reduction in power with accumulated dust density of 2 $g/m^2$. The cleaning frequency for PV modules in desert regions is about 20 days. Therefore, it's recommended that the PV modules cleaning can be determined as three weeks to keep the high power output. Main findings are presented as follows:

- The calculated cleaning time based on the present model agrees well with the related experimental results. Therefore, this verified method can be adopted in engineering application to estimate the cleaning frequency of dirty PV modules.
- The average particle diameters and tilt angles can significantly influence the required cleaning time because the deposition velocity is highly dependent on gravity. The cleaning time was decreased to 20 days from 6256 days with the increase of representative average diameter from 1 μm to 20 μm and, was increased to 78.2 days from 20.2 days with the increase of the inclined angle from 0 degree to 75 degree, respectively.
- Wind velocity has little effects on the required cleaning time because the average diameter belongs to the coarse zone even though it can increase the deposition velocity of the particles in the fine zone.
- Considering the natural cleaning effects of rainfall and wind, this model is more accurate for desert environment where precipitation and wind resource are

extremely scarce.

## 7.5 Recommendations for future work

Even though some issues for dust accumulation process on PV modules have been investigated in this thesis, due to the limitation of time and facility, more work is necessary to study in the future.

For the influence of temperature differences and generated current on dust accumulation process, the conclusions of these two parameters are opposite. So, an interesting question should be answered that the combination effect of these two parameters of operating solar PV modules and which one can lead to larger impact. To solve these two problems, field studies with indoor experiments should be designed and conducted. Moreover, the equation to effectively calculate the influence of generated current needs to be developed by measuring the actual deposition velocity and the charge distribution of dust particles. In addition, dust accumulation process on solar PV modules can be greatly affected by other significant deposition mechanisms, such as gravity force or other diffusion forces. So, the comparison of temperature differences and generated current with other deposition mechanisms will be studied in the future.

In addition, even though the required wind velocity for dust removal has been calculated based on the particle resuspension model, the cleaning efficiency of one specific wind velocity for particles with different diameters is not clear. So, the cleaning performance of different wind velocities needs to be investigated based on indoor experiments and numerical simulation method. Furthermore, the method for evaluating the distribution of dust particles needs to be further studied based on the known particle deposition model and resuspension model. Last but not least, the method for calculating reasonable cleaning frequency for other environments should be developed according to considering the cleaning impact of wind or rain and the compositions of dust particles due to different origin mechanisms.

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