Self-cleaning surfaces for solar energy applications

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Abstract of the Thesis

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Dust and organic contaminants accumulated on the solar panel can block solar irradiation. Consequently, the solar panel output efficiency is reduced dramatically. The purpose of this thesis is to study an efficient method to remove the organic contamination and dust deposition on the solar panel using a self-cleaning surface.

It was discovered that organic contamination on the self-cleaning glass was decreased by 95% in 5 minutes by exposure to 5000w/m^2 of UV. To study the dust deposition process, a dust storm simulation box was made. It was found that dust deposition was a function of solar panel inclination angle, with larger inclination angles reducing dust deposition. However, the self-cleaning glass did not have detectable effect on dust deposition.

Dedication Page

Dedicated to my parents.

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List of Abbreviations

Include this list if applicable.

PV: photovoltaic

UV: ultraviolet

CSP: concentrating solar power

FTIR: Fourier transform infrared spectroscopy

IR: Fourier transform infrared spectroscopy

UV-Vis: Ultraviolet–visible spectroscopy

EDS: Electrodynamic Dust Shield

AC: Alternating current

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The thesis is dedicated to my parents, Wenjie Zhang and Jieyu Shang, for their unconditional support and love.

1 INTRODUCTION

One of big challenges of the society is to find sufficient renewable energy for the future. As tech developing, windy power, solar power, and hydropower are decent candidates. However, most of them have severe disadvantages. Windy power, which is the use of air flow through wind turbines to generate electric power, shows an excellent performance about energy output at a windy area. However, noise disturbances and destroyed zoology can be a disaster to the local environment. Therefore, places, selected to build windy power, are rare. Hydropower, a power derived from the energy of falling water or fast running water, is clean, safe, and reliable. However, the disadvantages are the unknown environmental consequence, seasonal dependence.

Solar power comes from solar irradiation. Solar energy can be a significant candidate due to huge irradiation from the sun. Covering 0.16% of the land on earth with 10% efficient solar conversion system would provide 20 TW of power, nearly twice the world consumption rate of fossil energy[1]. After transformation technology, the nature sunlight can be used as the form of electronic power. Currently, owing to people's demand for cleaning and sustainable energy, solar energy draws more and more attention.

The solar energy can be harness by two ways: concentrating solar power(CSP) system and Photovoltaic(PV) system. CSP system absorbs solar energy and convert it to heat that can be used to motivate stream-driven generator. This energy can be further transformed into electric form. PV system directly transforms solar energy into electricity. Comparing this two transforming process, it can be concluded that the PV system has a better efficiency. And the CSP system needs the access to water resource, which can cause a waste, especially at desert.

At this thesis, the PV system is selected as the topic. However, due to some reasons, PV system transforming efficiency is decreasing gradually, compared with the original value. The most common one is the aging effect, which cannot be avoided. Another significant reason is that the PV system is blocked by some covering, which can be avoided or cleaned, on the surface.

Thus, to increase the efficiency of PV system, there are two methods. The first one is to upgrade the semiconductor materials, related with PV system. However, the relative efficiency research has been limited to 15%-20%. The second one is to increase solar irradiation collection ability, such as improving glass's transparency by reducing iron content. The most important factor in the performance of a flat plate solar panel, no matter for the photovoltaic or thermal collector, is the amount of solar irradiation that reaches PV system. Solar irradiance on a panel varies with geographic location, time, and the orientation of the panel about both the sun and the sky.

The aim of this thesis is to prepare self-cleaning membrane on the glass and test the effect of this layer on organic contamination and simulate the dust storm in simulation box to find whether the self-cleaning membrane also has an effect on dust deposition.

2 REVIEW OF LITERATURE

2.1 Common problem

The most important factor for the performance of solar panel is the amount of solar irradiation that reaches it. However, due to environmental or natural affection, solar panel's radiation collection cannot achieve what's expected. At this part, the problems, which affect solar radiation, are discussed.

2.1.1 Sun-track loss

The solar irradiation information is calculated based on the horizontal surface, while the solar panel is usually fixed at an angle to the horizontal plane. Therefore, a lot of radiation energy can be wasted due to unmatched direction, as Figure 2-1 shows. To maximize solar efficiency, a tracker is needed. However, the energy used for tracker should be lower than power increased by the tracker.

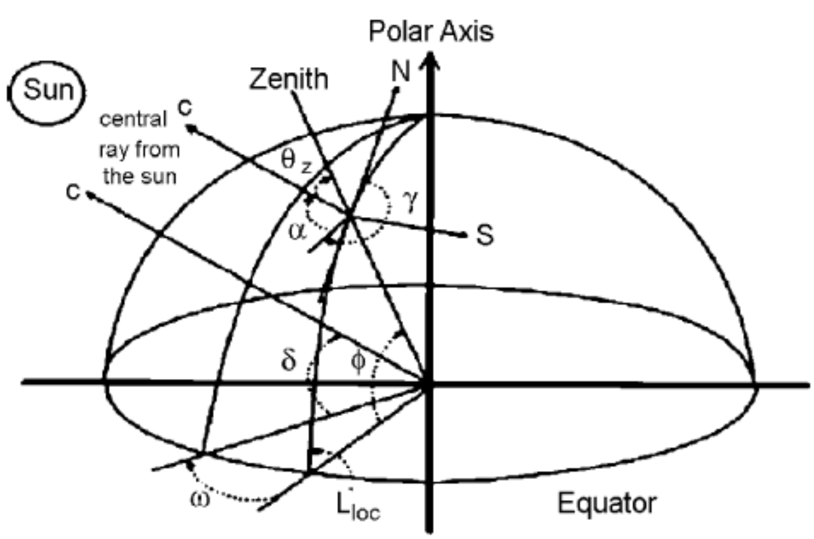

Figure 2-1 Schematic representation of the solar angles[2]

2.1.2 Shading loss

Shading loss happens when the solar system is shaded by nearby objects, like building and trees. Since the output power is influenced by solar irradiation, a reduction of input energy would impede the performance of the solar panel.

Shading loss is avoidable if the solar panel is installed at an unshaded place, such as roof, desert. However, a better installing place always introduces a severer environment, which brings solar panel soiling loss problem.

2.1.3 Soiling loss

Soiling loss means the loss in PV system caused by snow, dirt, dust or some other particles that block the surface of PV system from irradiation absorption. These small particles are in the form of thin covering on the solar panel. This typical particle size is less than 10μm in diameter, but it also depends on location and the surrounding environment. When dust particles, carried by the wind, finally settle down on the surface of PV device, the efficiency of this system can drop due to obscure, especially in a dry environment. Mazumder[3] found that the PV system efficiency can drop by 40% with just $4g/m^2$ of dust. Dorobantu et al.[4] found that the pollution and particles, created by traffic or nearby agriculture, accumulate rapidly and can impede the efficiency of the solar transformer by 20% during dry summer conditions. Further, they also found that an extremely thin layer of particles can reduce the solar output by almost 40%. Zorrilla-Casanova et al.[5] found that the average loss of energy caused by pollution and particulate matter can reach 4.4% in a year. Under dry conditions, the daily energy loss can be higher than 20% of the area without regular rainfall. Simulated experiment by Sulaiman et al.[6] using artificial dust, made by mud and talcum, along a stable irradiation source shows that the cumulated dust on the solar panel can decrease the solar output efficiency by up to 50%.

Kimber et al.[7] found that the average loss of solar output efficiency is around 0.2% per day in a dry environment without rainy weather. The daily energy loss causes an around 56.2% power loss for a year. Mavroidis et al.[8] found that both dirt and dust particles have the same ability to block out the solar irradiation and reduce the solar efficiency. Boykiw[9] found that dust and dirt accumulation on the solar panel can cause a 5-6% decrease in energy output efficiency in one week.

Essalaimeh et al.[10] studied the effect of dust deposition on the solar system installed in Jordan and found that PV system with dust deposition output efficiency is less than a cleaned PV system with 31-35%.However, Elminir et al.[11] studied the decreasing effect of dust on the solar system in Egypt, and found that, in a 45° angle facing south solar cell, this system output efficiency decreased around 17.4%/month. While Kymakis et al.[12], on the island of Crete, found that the annual power loss is 5.86% due to the dust deposition.

From these references, it can be found that soiling loss causes a lot of energy loss as deposition accumulating. Even a thin layer of deposition(4g/m^2) bring a huge efficiency reduction (40 %). Therefore, cleaning the surface deposition layer is significant.

2.2 Sun-track system

Solar panel always works in a fixed direction, which causes a mismatch with solar irradiation direction at the most time of a day. An efficient way to solve this problem is to change solar panel direction based on time, season, latitude and longitude. This part discusses tracking system and efficiency gain.

2.2.1 Energy gain in tracking system

The solar tracking device can be classified by one-axis tracker and two-axis tracker. Two-axis tracker, known as its higher accuracy, have two types: polar(equatorial) tracker and azimuth/elevation (altitude-azimuth) tracker.

The solar tracker is a device to keep the solar panel or PV system being in a perpendicular position to the sun irradiation direction during the daytime, to maximize the sunlight collection. Finster introduced the first solar tracker in 1962, and one year later, Saavedra developed an automatic controlling machine to orient an Eppley pyrheliometer[13].

Solar trackers do not need to point to the sun directly. If the mismatch angle is less than 10°, the output still can reach 98.5% of the full-tracking maximum. In general area, annual gain by using solar tracker is between 30%-40%. Even in the cloudiest area, the annual gain can reach 20%. The daily gain in any location can vary from 0 to 100%[14].

Tomson[15] studied the separate two-positional tracking concentrator, which is around a single axis. The collector rotated around its single tilted axis per day with predefined deflection angles, as Figure 2-2 shows. It was concluded that using a low-energy tracker, with limited movement per day, increased the seasonal collecting efficiency by 10-20%, compared with a fixed south-facing PV system tilted at an optimal angle.

Agee et al.[16] studied the different tracking technologies, their associated cost, the device maintenance, and the efficiency improvement. It is concluded that the tracking system based on hydraulic technology works well for low capacity installations. They also found that polar-axis tracker had a good performance as well as two-axis type, while its cost was close to that of single-axis tracker.

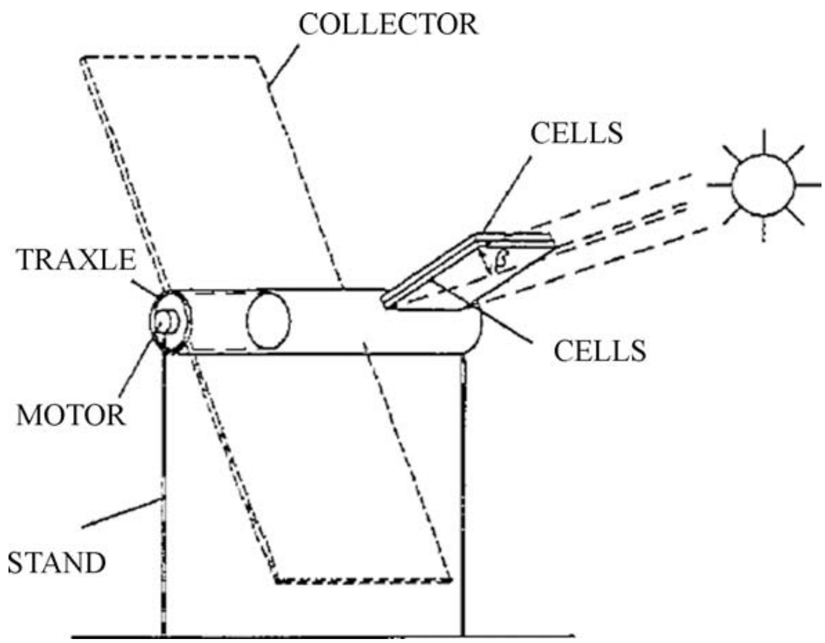

Figure 2-2 Horizontal axis tracker[17]

Ai et al.[18] studied and compared the azimuth and hour angle three-step trackers. They divided the daytime into three equal parts to adjust the tilt angle. They found that the optimized inclination angle was 30.2% for the whole year, while the two-axis azimuth three-step tracking was 72% higher than the horizontal surface. By comparing between one-axis azimuth, three-step tracker and hour angle three-step tracker, there's no significant difference in efficiency.

Michaelides et al.[19] studied and compared solar water heater in four different surfaces: fixed at 40° from the horizon, single-axis tracker, fixed slope and variable azimuth and seasonal tracking way where the collator changed twice per year. To analyze the result, they used computer simulation for the thermal system, and the result showed that the single-axis tracking system had the best performance. In detail, the annual solar fraction in Nicasia with this mode was 87.6% compared to 81.6% with the seasonal method and 79.7% with the fixed surface.

However, the corresponding data for Athens were 81.4%, 76.2%, and 74.4%. Therefore, the fixed surface method was the best one if considering economic cost.

2.2.2 Passive(mechanical)) tracker

For this tracking system, normally they are based on thermal expansion of a materials or shape memory alloys. This kind of method is composed of a couple of actuators working against with each other. When the combination of actuators does not equal to zero, the unbalanced force pushes the device to a right direction until the actuators are balanced. Passive trackers, compared with active trackers, are less expensive and less complicated. However, the structure of passive tracker tends to work in low efficiency even stops to work at a low temperature.

Clifford et al.[20] developed a novel passive sunlight tracking system based on modeling data. This tracker had a significant corresponding force even though the deflection, the expanding metals generated, was small. They fixed two same bimetallic strips, made of aluminum and steel, symmetrically on the two side of the wood frame. When one side of bimetallic was shaded, the other end of the strip can absorb the solar radiation. They also added a damping system into the sun tracker to avoid oscillation and slow response. It was concluded that the computer modeling result is quite similar to the real experiment result, which had the potential ability to increase PV system efficiency by up to 23%.

Poulek[21] designed and studied a single axis passive sunlight tracking system by using shape memory alloy. The shape memory alloy can be easily deformed at relatively low temperature(70°C). Then it can return to its original shape by heating it above its transformation temperature. They concluded that the efficiency of shape memory alloy actuators is 2%, which is two orders of magnitude higher than that of bimetallic actuators.

2.2.3 Active(electrical)) tracker

The active tracker can be categorized as the microprocessor and electro-optical sensor based, PC controlled date and time based, auxiliary bifacial solar cell based and a combination of these three systems[22].

2.3 Cleaning techniques

From the previous discussion, it can be found that shading loss problem can be solved by installing PV system at an unshaded place and sun-track loss can be solved by using a tracker. However, sun-track system is not worth to install if considering economic cost. The soiling loss problem varies depending on different location, season, deposition constitute. And at this section, some cleaning method can be discussed.

2.3.1 Brush method

Moreno et al.[23] studied the effect of low mass dust wiper tech. They found that this automatic dust wiper can increase up to 7% of the PV output efficiency due to more irradiation absorption. It also can be concluded that removing dust with automatic robot method has a high initial and operating costs due to the complex mechanical and electric designs.

Kandil and Elsherif[24] developed several systems, used in PV panel self-cleaning system with water. The cleaning system can be separated into two parts, nozzles and brush. They used the fixed nozzles or a sliding set of nozzles as a water ejector, and they used a sliding brush or a rotating brush as the cleaner. They also found that the solar panel performance can be improved by cleaning the surface dust with this automatic system. However, even though this cleaning method had a good performance to clean dust, it needs a high-pressure water and brush to clean the sticky and muddy dust.

Dust suspension and deposition phenomenon is the commonest problem in all lunar and Martian devices. Fernández et al.[25] suggested using a series of the robotic wiper to keep PV sensor clean on Mars. This idea applied a light but robust actuator as the robotic wiper to protect the solar panel surface. They also studied one hundred wipers with different dust deposition level in a simulated Mars chamber. They found that even though all of the cleaning efficiency is higher than 93%, they suggested that the device was not recommended to be applied at an area more than 30 cm^2/ wiper because the power requirement to rotate the wiper was less than that value.

It can be found that brush method did not show a good performance without water. And considering the expensive robot, the method need to be further developed.

2.3.2 Electrostatic/electrodynamic methods

The method was introduced by Biris et al.[26,27], a researcher at NASA Kennedy Space Center and the University of Arkansas. EDS (Electrodynamic Dust Shield) is an effective dust removal technology. The EDS concept is based on the classic electric curtain theory. The EDS can be divided into two parts: multiphase electric curtain and single phase electric curtain.

Biris et al.[26] studied that the electrodynamic screen can be an efficient tool to prevent the dust from depositing on the PV system. And the result shows that the higher the voltage was, the better cleaning effect was. Bock et al.[28] and Sims et al.[27] found that voltage is the primary parameter to determine the cleaning efficiency of PV system. However, even at a low voltage, the electrodynamic screen also can remove part of the dust layer. But the general rule is that higher voltage leads to a better cleaning effect.

2.3.2.1 Multiphase electric curtain

Typically, an electric curtain is assembled by a set of parallel rectilinear and regularly spaced electrodes. All of the electrodes are located on the surface of protected solar panel and covered by a layer of insulating materials. As Figure 2-3 shows, the three-phase electric curtain, as the commonest multiphase electric curtain, consists of three “Combs” of interdigitated electrodes connected to tree different AC power supply with a phase shift of 2π/3 and 4π/3, which can generate a traveling wave. Owing to the continuing distance from electron, the electric field, above the surface of the insulating layer, is rotating. And the direction of traveling wave is from normal to electrode axis.

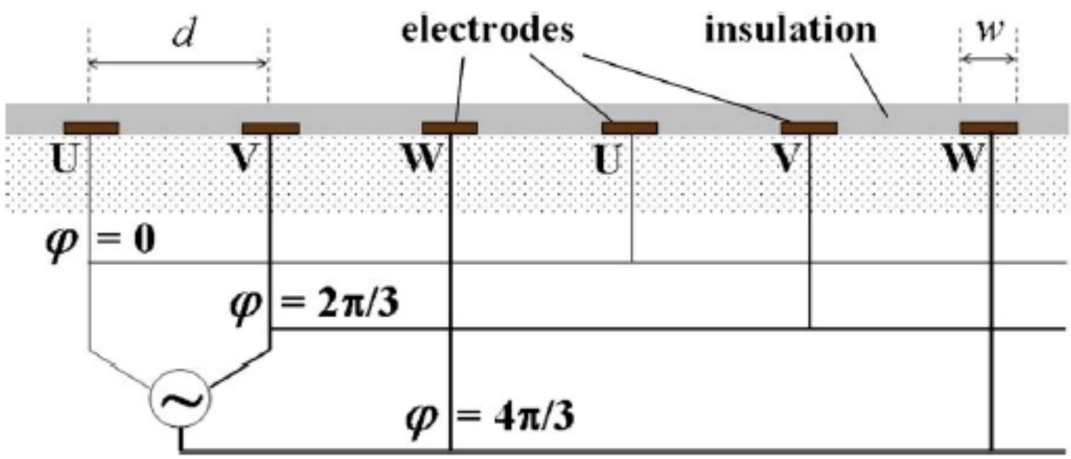

Figure 2-3 Cross section of a planar three-phase electric curtain[29]

2.3.2.2 Single phase electric curtain

Compared with previous one, the single phase electric curtain has a simpler structure, with only two interdigitated combs, as Figure 2-4 shows. One of the combs is grounded and the other one is supplied by an AC power supply. And also to increase the output efficiency, both of the combs can be provided with AC power supply, with a phase shift of π. The single-phase electric curtain can create a standing wave. At any point of the electric field, the charged dust is expected to oscillate with the direction of electric field, and for a precise moment, the electric field force is defined by the tangent line of the electric field. For the electric field, the amplitude depends on input power and distance between two electrodes. In theory, when a particle is smaller than the inter-electrode space, the spatially average force is zero, which cannot move particles. However, Masuda et al.[30] found that, in both standing-wave and traveling-wave electric curtain, particles of some components, like polyvinyl chloride(PVC), polyethylene(PE), nylon et al., can be quickly charged by contacted with insulated materials and easily be removed at a high voltage.

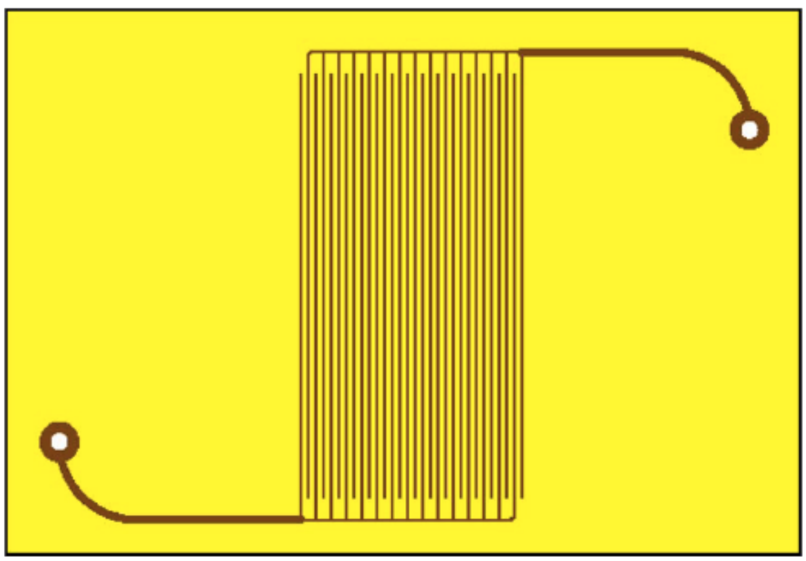

Figure 2-4 Single-phase electric curtain with the two "Combs" of parallel electrodes[29]

Sims et al.[27] used a set of electrodes to assemble a single-phase electric curtain, which is showed in Figure 2-4. Under air condition, the power supply, used to create standing wave, owns an up to 10kv voltage and tens to hundreds HZ frequency. After dust particles had touched the insulated surface, they were agitated, and the electric field cleans most of them electric force. The clearing efficiency, which can be calculated by the proportion of dust swept by the electric curtain, was increasing as the voltage increase. And they also found that the result was quite similar among three different samples: acrylic polymer, lactose, and a Mars dust simulant.

To make this work efficiently, the electron should be transparent to allow more solar light in. A low frequency and high AC voltages can make the clean ability better. Obviously, removing dust with the electrodynamic method has a high initial and operating costs. And due to lack of water in this process, the electrodynamic screen cannot remove every kind of dust, such as some muddy or even sticky dust.

2.3.3 Water

Mavroidis et al.[8] designed an automatic device, which is used to clean the solar panel surface with water spray. They also found that the PV system efficiency further increased up to 15% while the spray water cooled the device temperature down.

Zorrilla-Casanova et al.[5] also found that cleaning the PV system by washing was the most reliable and lasting method. However, cleaning vast area of the solar panel with water was expensive and wasteful, especially in the arid area. They found that rain water washing can also increase solar panel's efficiency by removing the covered dust. In rainfall period, even a light rain, 1mm was enough to clean the dust-covered solar panel. However, in a dry period without rain, like summer, the accumulation of dust particles can cause more than 20% daily loss.

Even though water shows an excellent property to remove dust. It's a huge waste especially for a large area not to mention desert.

2.3.4 Surfactants with electric charge

Abd-Elhady et al.[31] studied the ability of anionic and cationic mixture as surfactants to remove the dust particles from solar panel's surface. They found that the anionic materials of the surfactants can remove the negatively charged particles and the cationic part can pulse the negatively charged particles due to like electric charges repelling. It was concluded that the method of using a mixture of anionic and cationic had the best performance to remove charged deposited particles.

2.3.5 Water-repellent micro-shell structures

Park et al.[32] studied the super-hydrophobic microcell layer's ability to clean the solar panel surface, as Figure 2-5 shows. They found that non-super-hydrophobic structure sample's efficiency degradation was much faster than the solar panel, with a hydrophobic and water-repellent surface.

K.A. Moharram et al.[33] compared washing method and surfactant method[32]. They found that accumulation of dust on the solar panel can gradually reduce the efficiency of output and cleaning is necessary, especially in a dry and desert area. They also found that PV efficiency can decrease by 0.14%/day and up to 50% after 45 days when they clean the solar panel with non-pressurized water, which is concluded that clean the solar panel by only using non-pressurized water is not an efficient work. They also confirmed that the mixture of anionic and cationic surfactant could clean the surface of PV system and preserve its efficiency at a stable level. And also this combination surfactant can minimize the amount of water needed to wash the panel, and the mixture surfactant can save the energy, used for spraying the water. On the contrary, in the thin water layer, the sound pressure created possibilities to water spraying and not good cleaning effect.

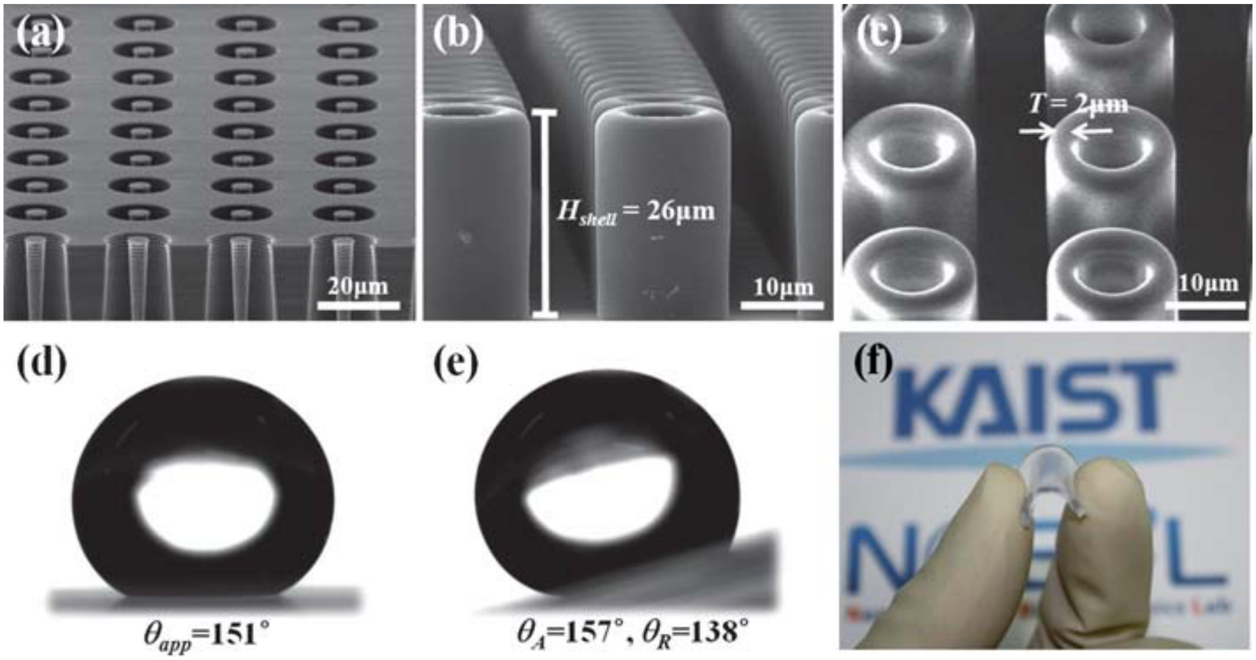

Figure 2-5 SEM images of (a) cylindrical silicon trench, (b) microshell PDMS array from the cross-sectional view and (c) side view. (d) Apparent CA of 151°was measured on microshell PDMS array with a water droplet (10 μL). (e) CA hysteresis of 19° was observed where advancing angle (Θ_A) of 157° and receding angle (ΘR) of 138_ were observed. (f) The sample of the microshell PDMS array was bent for demonstration of flexibility.

This a good choice to use super-hydrophobic structure avoiding dust deposition due to the economical cleaning process. And at experiment, contact angle was used to judge the coating surface property.

2.3.6 Ultrasonic system for solar panel cleaning

Over time, the PV system can be covered by dust, dirt, or even bird droppings. For most of the PV system, they are designed to work for 30 years and more. In a desert, the solar panel needed to be cleaned twice a year to maintain output efficiency at an acceptable level.

Vasiljev, Piotr, et al.[34] studied the ultrasonic system for solar panel cleaning theory by modeling with FEM software COMSOL. They also develop an ultrasonic cleaning system. They assumed that the numerical and measured resonance frequency are close. They also found that gap between the cleaning system and solar panel surface depended on expected water layer thickness. At this experiment, the thickness was from 0.5 to 1.5mm. For a thick layer, it needs more strong water flow, but it was more easy to create bubble cavitated flow.

2.3.7 Tilt

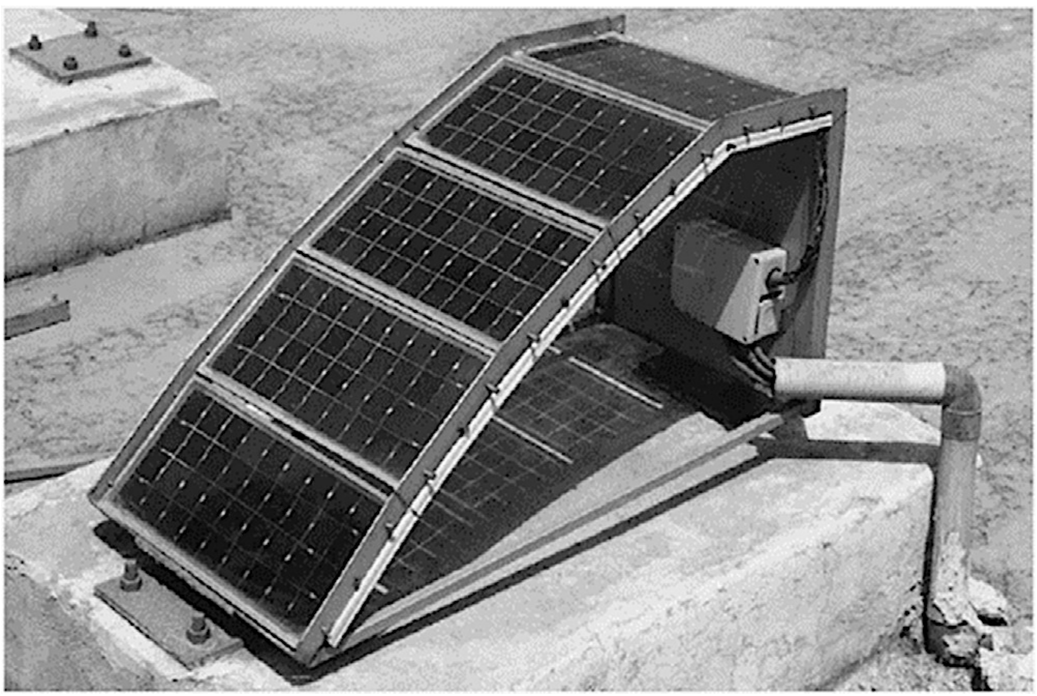

Figure 2-6 Five monocrystalline modules mounted with tilt angles of 0, 23, 29, 35 and 42°[35]

In the study by E. Asl Soleimani et al.[35] in Iran, Tehran in 1999, the investment was about the air pollution's influence on the efficiency of PV system. Owing to the cars and local industries development, local PV working efficiency is impeded. Thus, researchers wanted to improve the energy output without increasing solar panel area or number. The experiment system, working with few different inclination angles, was conducted on the roof of the University of Tehran, which is showed in Figure 2-6. The result indicates that the output of this series of PV system varied in different seasons owing to the varied pollution in various seasons. In winter, the air density was the largest, due to the most severe pollution over the whole year, which caused the reduction of radiation absorption and as a result, the output efficiency decreased. In fall, the windy weather made the pollution go away, which led to a better efficiency. In spring, PV system had the highest efficiency as the inclination angle increase, since the dirt and dust were washed by the rainy weather. In summer, the output's efficiency was between spring's and fall's. And the result showed that the PV system output efficiency could drop more than 60% since the solar irradiation was blocked by covered dust.

At experiment part, the tilt method was used to compare different angle sample's dust deposition weight. It's found that the slope can make dust drop and make the transmittance increase.

3 EXPERIMENTAL METHOD

The experiment consists of two parts, organic contamination part, and dust deposition part. To simplify the experiment, Guardian's ultra-white glass replaces the solar panel as the sample. Transmittance and deposited dust weight are two leading indicators to represent clean degree on the sample surface. The experimental goal was to find an efficient method to clean both organic contamination and dust deposition.

3.1 Self-cleaning coating

The self-cleaning solution, which consists of TiO_2, was provided by PureTi Company. When TiO_2 is exposed to the ultraviolet beam, it has an active catalytic property, which can be used to clean organic contamination. On the other hand, TiO_2 surface topography changes when the TiO_2 atoms are activated by the ultraviolet beam. And the modified surface topography is expected to decrease dust deposition. Figure 3-1 shows the difference between uncoated sample's surface and hydrophilic surface. And hydrophilic surface seems easier to be cleaned.

3.1.1 Coating method

To coat solution uniformly on the sample, spinning coating method was selected as the coating method. Also, the industrial coating method was compared with the spinning coating method, which is showed in Figure 3-2. It is found that that spinning coating is repeatable and controllable. However, spinning coating only can be applied to a small sample. On the contrary, the spray gun method can be applied to a larger area. The spin coating parameters were as following:

- Speed: 2500 rpm
- Time of rotation: 30 s

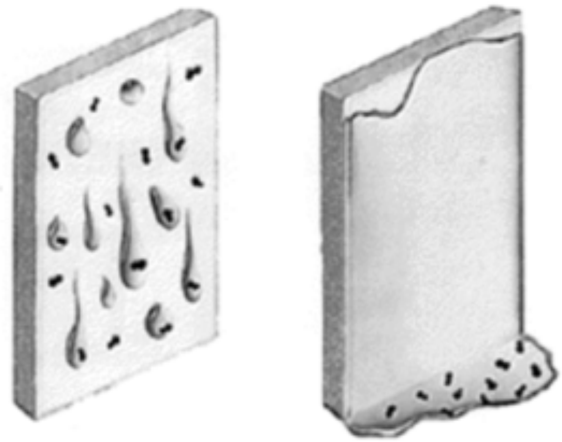

Figure 3-1 Illustration of uncoated and coated tile with a hydrophilic TiO2 layer[36]

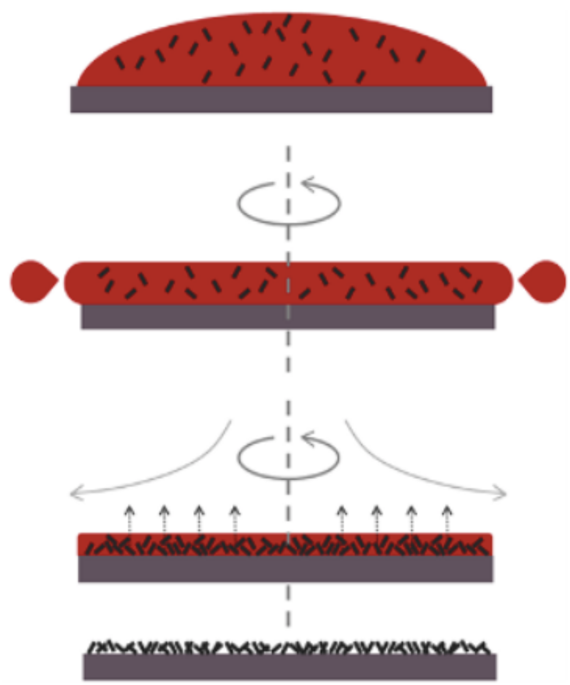

Figure 3-2 Schematic illustration spinning coating

3.1.2 Sample preparation

At this experiment, the sample substrate was ultra-white glass, which replaces the solar panel. The size of the glass was $2x2cm^2$. The stearic acid of 97 % purity, which was from Acros Organics through Alfa Aesar, was used as organic contamination. The solvents used for the preparation of the solutions were ultra-pure water from Direct-Q 3 Millipore system and absolute ethanol from SDS.

The Self-cleaning solution was deposited on the glass substrate by spinning coating. Several different-layer samples were compared by contact angle and transmittance. For the one-layer sample, stearic acid solution (10 g/L in absolute ethanol) was deposited on it by spin coating method.

3.2 dust simulation

To test cleaning efficiency to dust, the simulation about dust deposition process is necessary. And the simulation problem can be divided into three parts: dust, sample holder, and simulation box.

To simulate nature dust, Sahara Desert's aerosols particle, which is around 10-50 µm, is selected as the reference. The sand was collected from the nearby beach and then was ground until the dimension was close to desert's size by using a sieve. The sieve's aperture size was 38µm, which allowed dust with a less-than-38µm diameter and dust with slender form in. Therefore, the particles' diameter can be around 38µm.

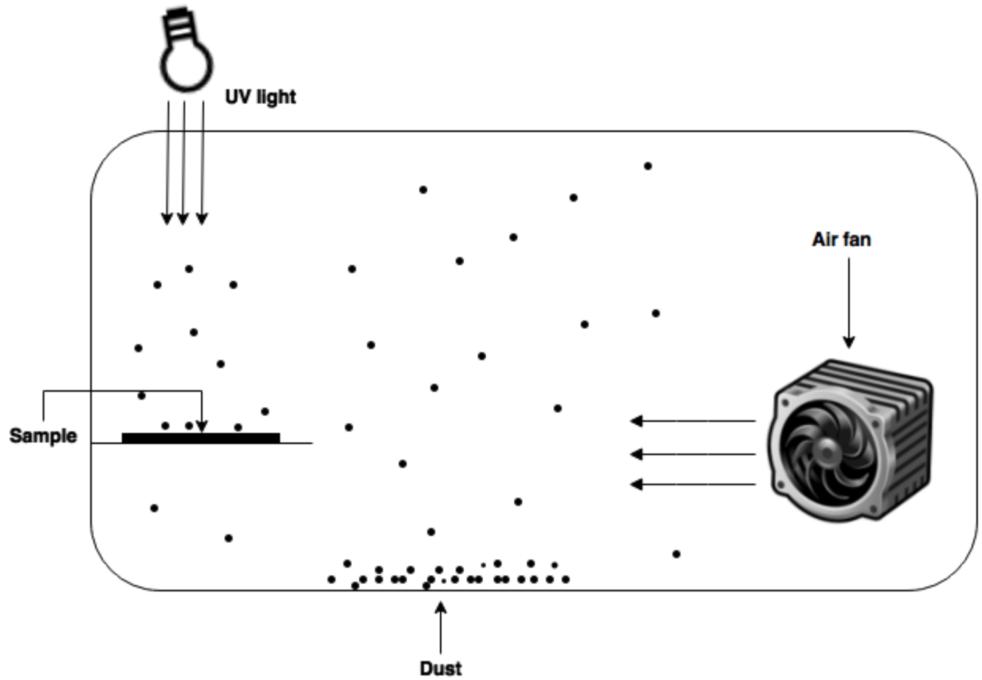

Figure 3-3 Schematic illustration of dust box

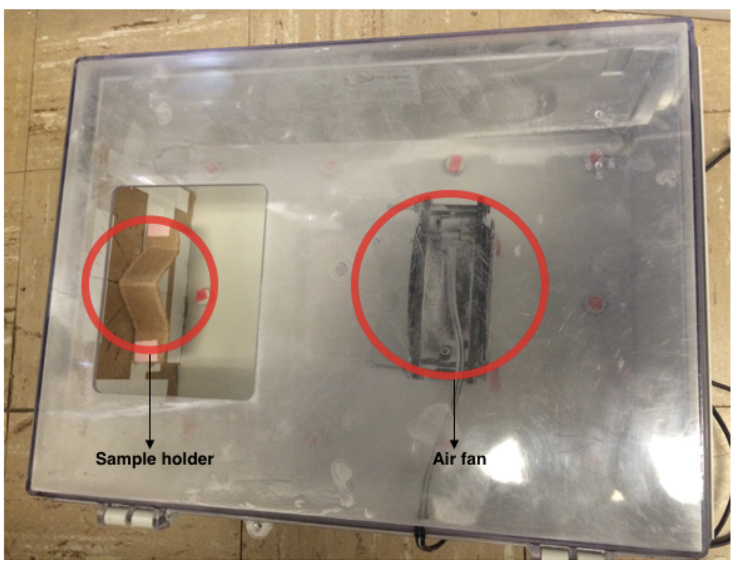

Figure 3-4 Dust box

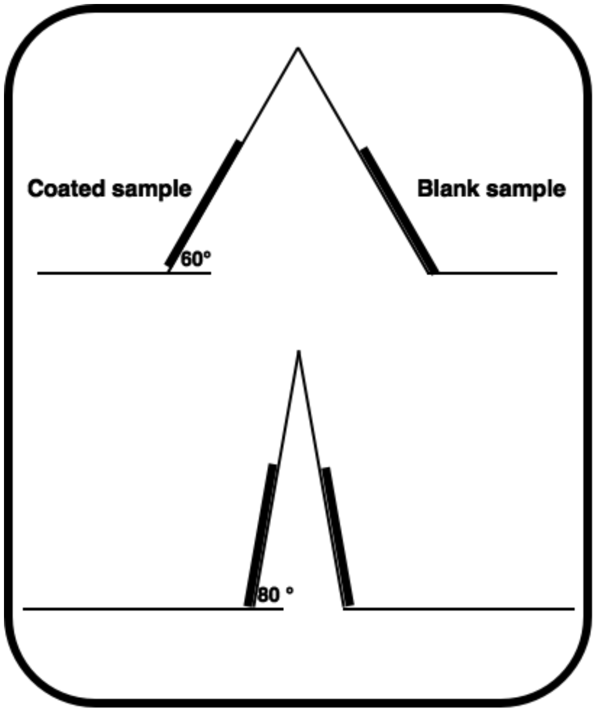

Figure 3-5 Illustration of sample holder

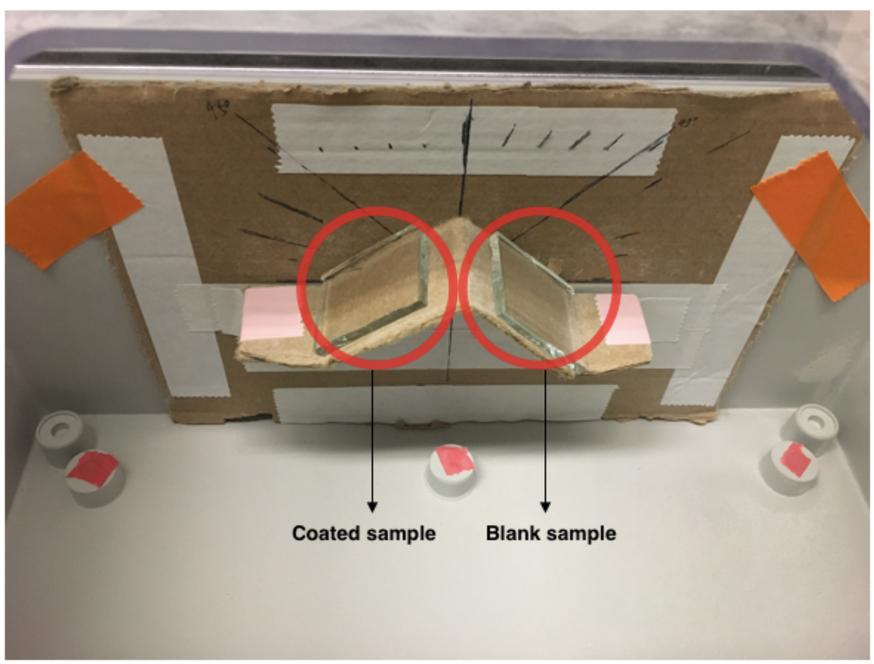

Figure 3-6 Sample holder

About the simulation box, the primary function was to simulate the process of dust floating and settling down. Figure 3-3 and Figure 3-4 show the dust box, which consists of air fan, sample holder. The dust was floated by air fan and when dust was far away from air fan, the gravity can make it settle down. However, as the simulation time increased, more and more dust was fixed at corner. To keep simulation environment being equal, the box should be cleaned after simulation and the same weight of dust should be added to box center before next time. From Figure 3-4, The hole above sample holder was used to maximize ultraviolet radiation into the box. When the whole system worked, the hole was covered by a piece of ultra-white glass, as this glass transmittance was much better than the box.

The sample holder is showed in Figure 3-5 and Figure 3-6. The symmetrical structure of sample holder was used to compare the coated sample and uncoated sample. The left sample was coated sample, and the left sample was a blank sample. Before test, the comparison result was expected that coated sample had a better performance than uncoated sample, which means that coated sample should have less dust deposition. To keep both two sample were under equal condition, left and right inclination angle should be equal. Figure 3-7 shows the UV light.

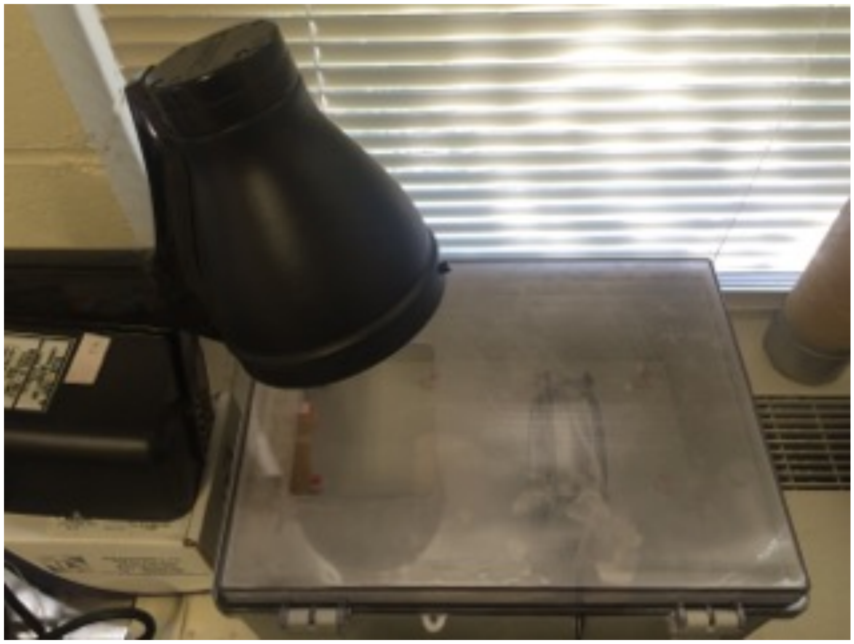

Figure 3-7 UV light above the dust box

3.3 Test

At this part, the self-cleaning property was tested. The first part was about stearic acid degradation test, including IR, UV-Vis. The second part was about dust simulation, including contact angle, SEM, inclination angle test and dust weight test

3.3.1 Contact angle

The contact angle is an angle between the liquid-vapor interface and the solid surface. It quantifies the wettability of a solid surface. Usually, when contact angle reaches nearly 0 degree, the solid surface can be seen as a super-hydrophilic surface. On the contrary, when the contacts angle of droplet exceed 150° and the roll-off contact angle hysteresis is less than 10°. Park et al.[32] found that hydrophobic and water-repellent surface can be a protection for the PV system efficiency. Therefore, Ultrahydrophobicity is a significant property to increase the solar panel efficiency. To find the self-cleaning coating's effect on the sample surface, several different layers coating were test by contact angle.

3.3.2 UV-Vis

Ultraviolet-visible spectrophotometry is used to test the absorption spectroscopy and reflectance spectroscopy in an ultraviolet-visible spectral region. In this experiment, UV-Vis (Thermo Scientifc Evolution 300) was used to test the sample's transparency, which represents the efficiency of the solar panel. The spectral range was from 200 to 1000 nm. The air's transmittance was set to 100%.

At UV-Vis spectrophotometry, the sample should be vertical based on the light path. However, the dust can fall out from the sample when the sample is vertical. To avoid this situation, another price of glass was covered on the sample and fixed by tape.

3.3.3 Inclination angle

The gravity can make dust settle down. Before the experiment, there was an assumption that the deposition dust would be less when a sample was inclined at some angle due to gravity. For this test, it was studied that whether the inclination can affect the dust deposition, by observing the change of sample's transmittance and deposited dust weight.

3.3.4 FTIR

Fourier transform infrared spectroscopy is a technique to obtain an infrared spectrum of absorption or emission. In this experiment, stearic acid was coated on the surface of glass sample as organic contamination and Nicolet 6700 FTIR (Thermo Scientific Inc) was used in transmission mode for quantitative analysis of stearic acid degradation. The spectral range was from 4500 to 450 cm^{-1}. The power of UV light was $5000 w/m^2$. And stearic acid has a characteristic absorption peak in FTIR technique. Therefore, by detecting the peak intensity of stearic acid, stearic acids cleaning efficiency can be found.

The sample coated with stearic acid was exposed under UV-light for five minutes. To examine the degraded stearic acid, the sample's IR spectrum was tested every minute.

3.3.5 SEM

Scanning electron microscope is a type of electron microscope that forms an image of sample's surface by scanning with a focused beam of electrons. The sample should be conductive to be detected by an electron beam. For this experiment, SEM was used to form the image of simulated dust and dust from Africa.

4 RESULT AND DISCUSSION

4.1 contact angle

As Figure 4-1 and Table 4-1 shows, contact angle varies with a different surface. It can be found that stearic acid layer leads to a large contact angle compared with coated sample. For coated sample, as the coating layer increases, contact angle decreases, which means that coating layer can make the surface of the sample more hydrophilic.

However, from chapter 2 discussion, a hydrophobic and water-repellent surface can clean the surface dust automatically, while the coated sample surface did not show a hydrophobic property due to a small contact angle. In theory, the coated sample did not have self-cleaning property aiming at dust deposition.

Coating layers	Left angle(°)	Right angle(°)
0	43.30	44.52
1	38.44	41.26
2	36.12	35.74
3	32.92	30.29
4	34.03	31.74
5	32.38	30.15
Stearic acid	67.24	68.88

Table 4-1 Contact angle with different surface

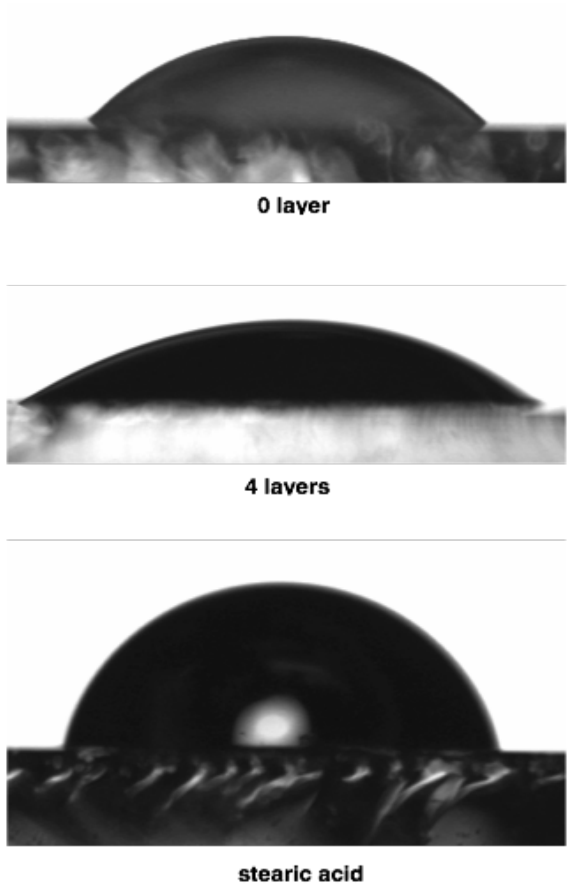

Figure 4-1 Contact angle

4.2 UV-Vis

Figure 4-2 shows the transmittance result about different coating methods. The x axis represents the wavelength and y axis represents the percentage of transmittance compared with air. The black line represents the sample coated from PureTi by spray gun coating. And the red line is one-layer sample given by spin coating. It can be found that the transmittance of black and red lines overlap with each other. And the solution was same. Therefore, it can be concluded that the thickness of sample layer in the spinning coating and spraying coated sample were same. Then one-layer sample can replace the sample coated by spray gun.

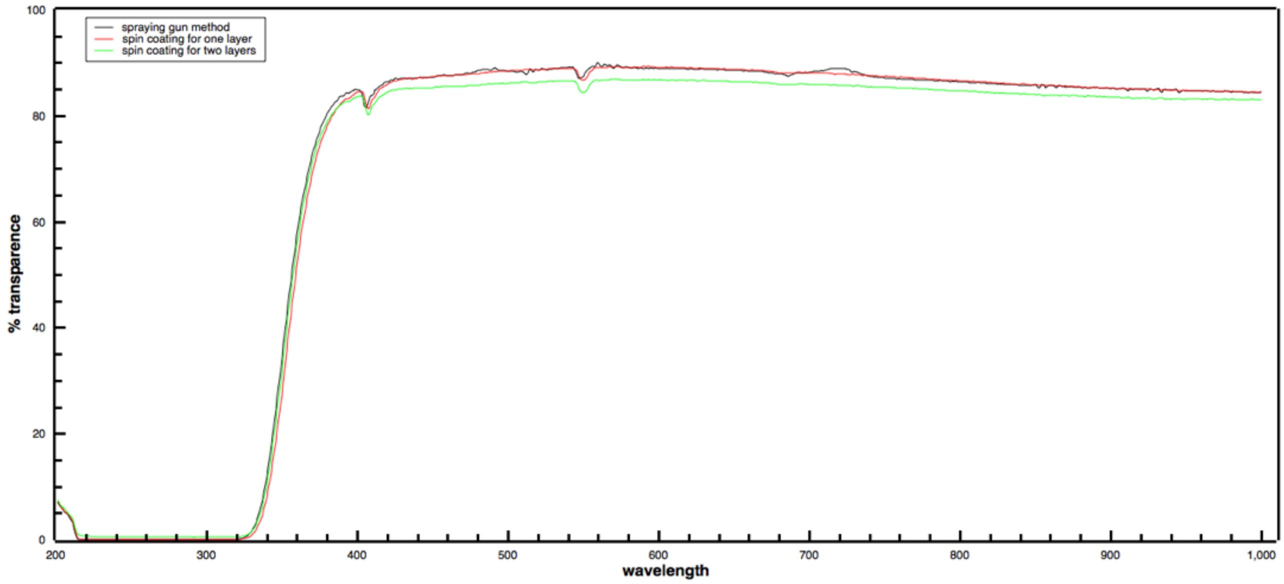

Figure 4-2 Transmittance comparison between spray gun coating and spinning coating

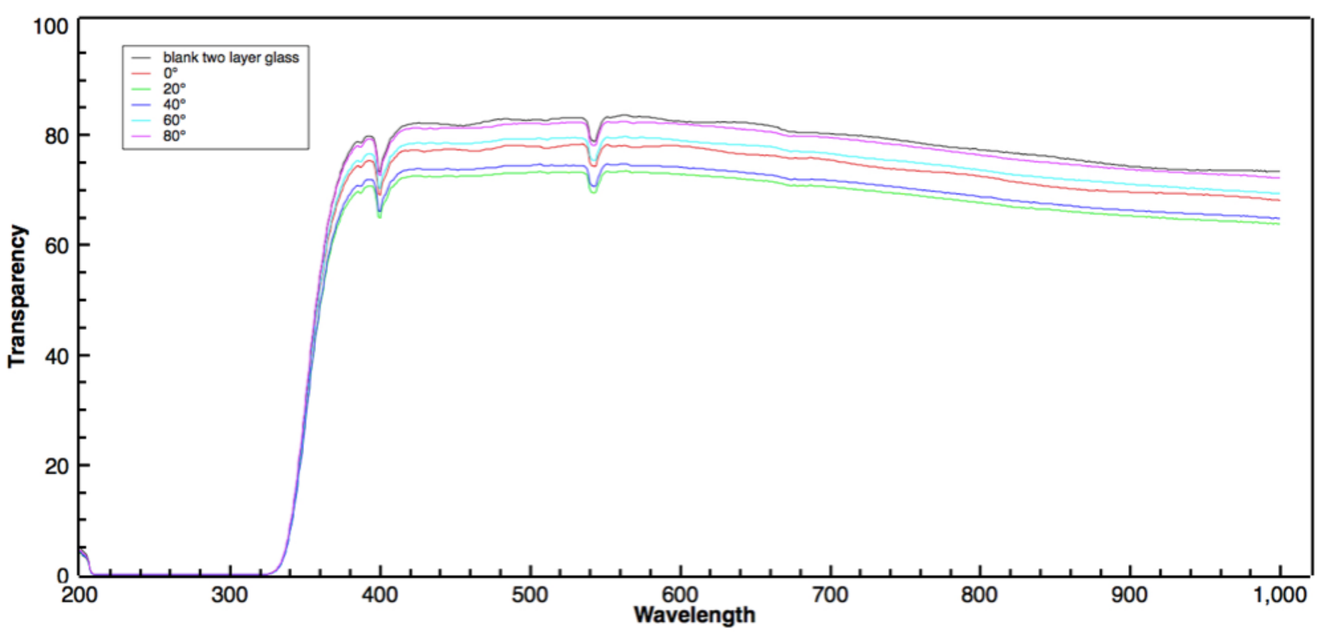

Figure 4-3 Different layers sample's transmittance

A double-layer glass sample replaced one-layer glass to avoid dust falling out of sample. For Figure 4-3, it was tested when samples are in different angles. It can be found that, as the sample inclination angle increased, the transmittance also increased, which means that slope can decrease the dust deposition effect. The 80° sample's transmittance nearly reached the blank sample and the reduction from 80° sample to 0° sample was around 15%, which indicated that vertical sample could efficiently impede dust deposition.

4.3 IR

The self-cleaning properties of the PureTi coating was assessed by degradation of stearic acid. Figure 4-4 shows the stacked FTIR spectra of the stearic acid as a function of UV exposure. The x axis is wavelength and the y axis is absorption intensity. A higher y value means more stearic acid. It can be concluded that stearic acid was substantially cleaned under UV light due to significant reduction in intensity of characteristic peak over the course of UV exposure.

The signals range of the symmetric and asymmetric CH stretching mode of the CH2 groups are between 2849 and 2916 cm^{-1}. Therefore, the degradation rate was calculated by integrating the absorbance of stearic acid between 2800 and 2975 cm^{-1}, which showed that after being exposed to UV light for 5 minutes the left stearic acid intensity was around 5% of initial value.

Even the power of light source was higher than the power of sunlight, which is from several hundred to one thousand based on location, season and weather, the cleaning performance is excellent.

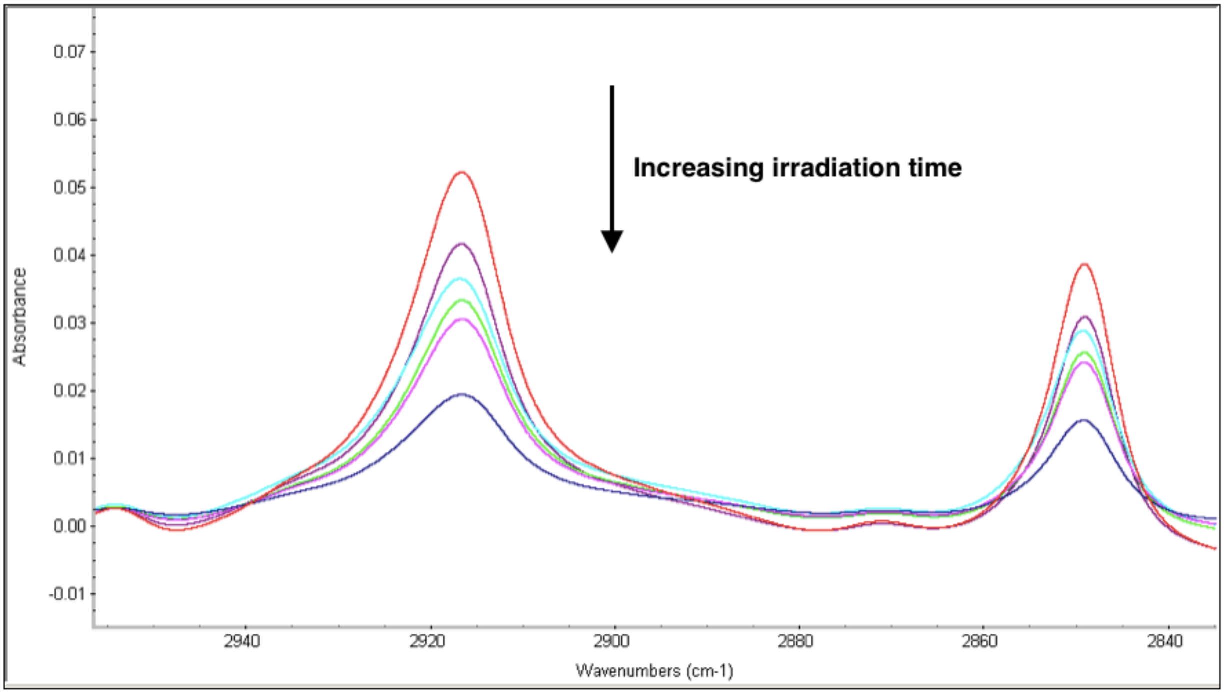

Figure 4-4 Degradation of stearic acid

4.4 SEM

Figure 4-5 shows Simulated dust. Figure 4-6 and Figure 4-7 show Africa dust. And we can find that the size of simulated dust was close to the real dust particles.

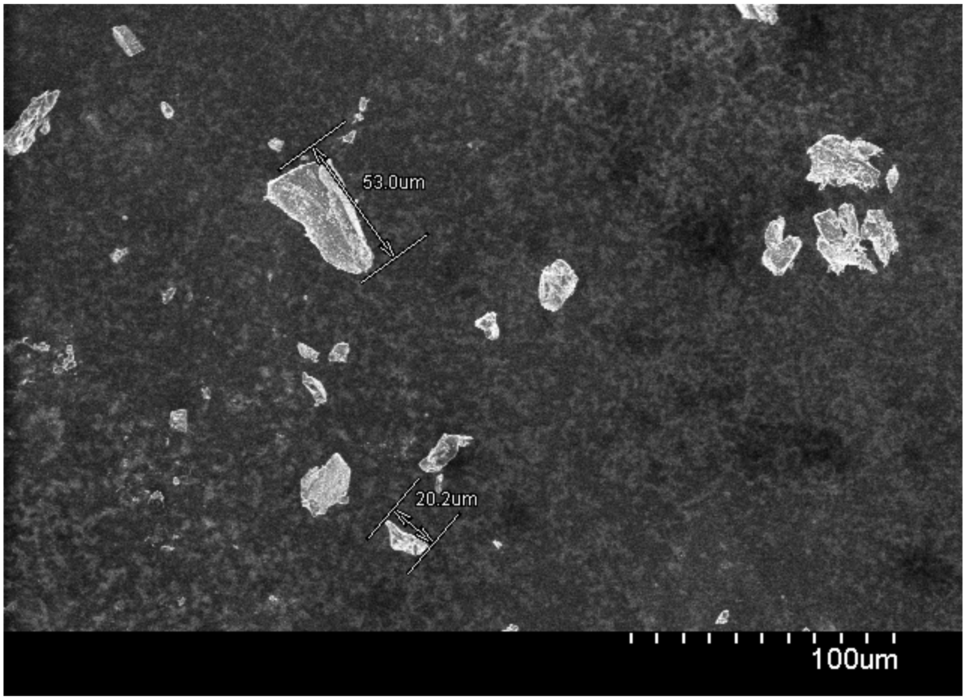

Figure 4-5 Simulated dust

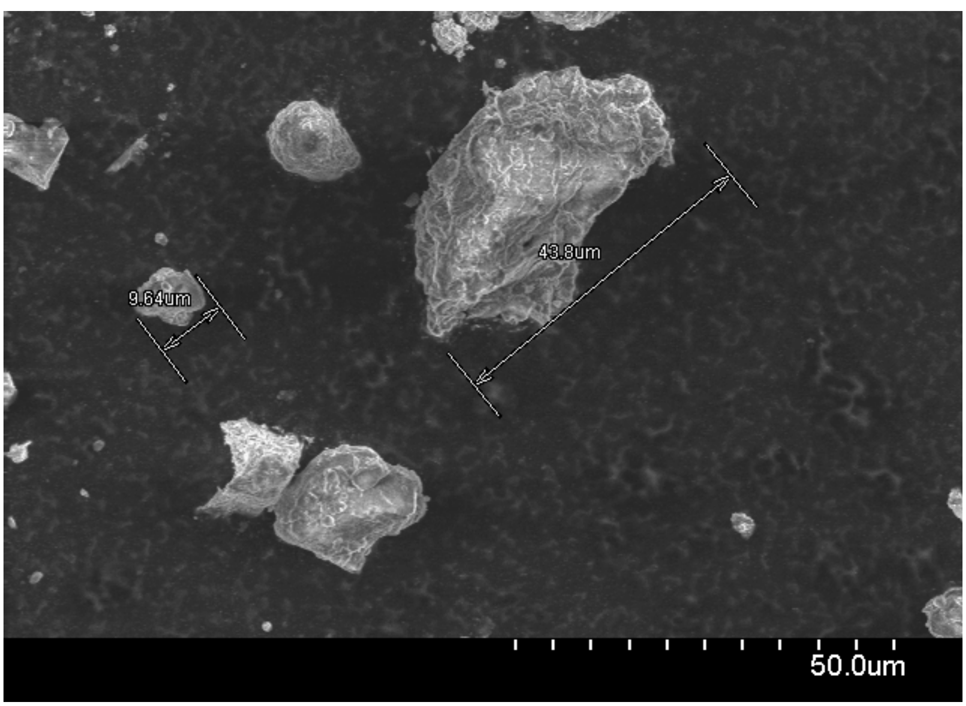

Figure 4-6 Africa dust

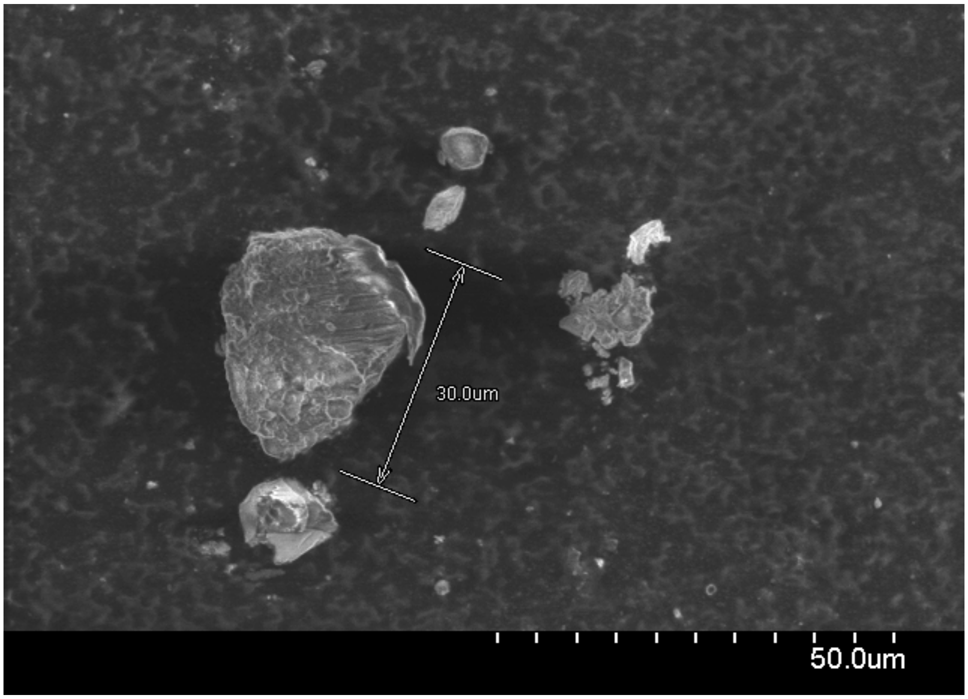

Figure 4-7 Africa dust

4.5 Weight test

Deposited dust weight of the blank sample, coated sample under dark environment and coated sample under UV light were studied. Deposited dust weight was used to represent the self-cleaning property. Each simulation time was 15min. Also, to discover the inclination angle influence, each sample was simulated at 5 different angles from 0° to 80°. The result is showed in Figure 4-8, Figure 4-9 and Figure 4-10.

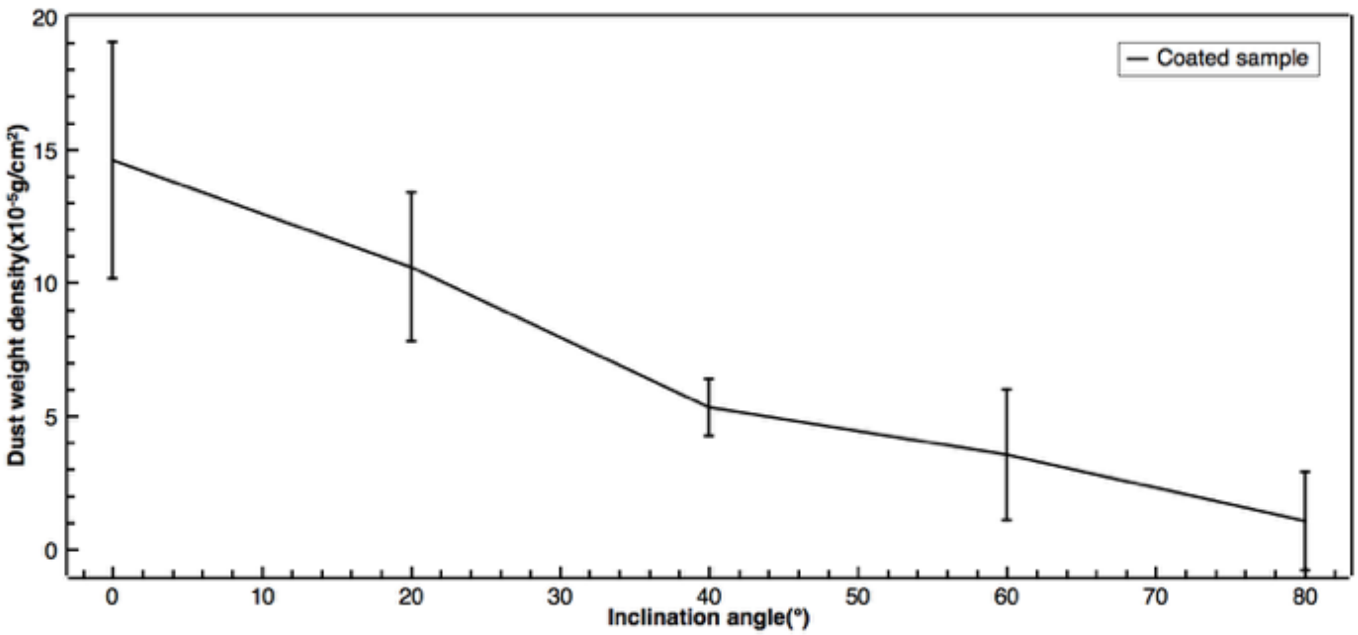

Figure 4-8 Dust weight density vs. inclination angle for coated sample

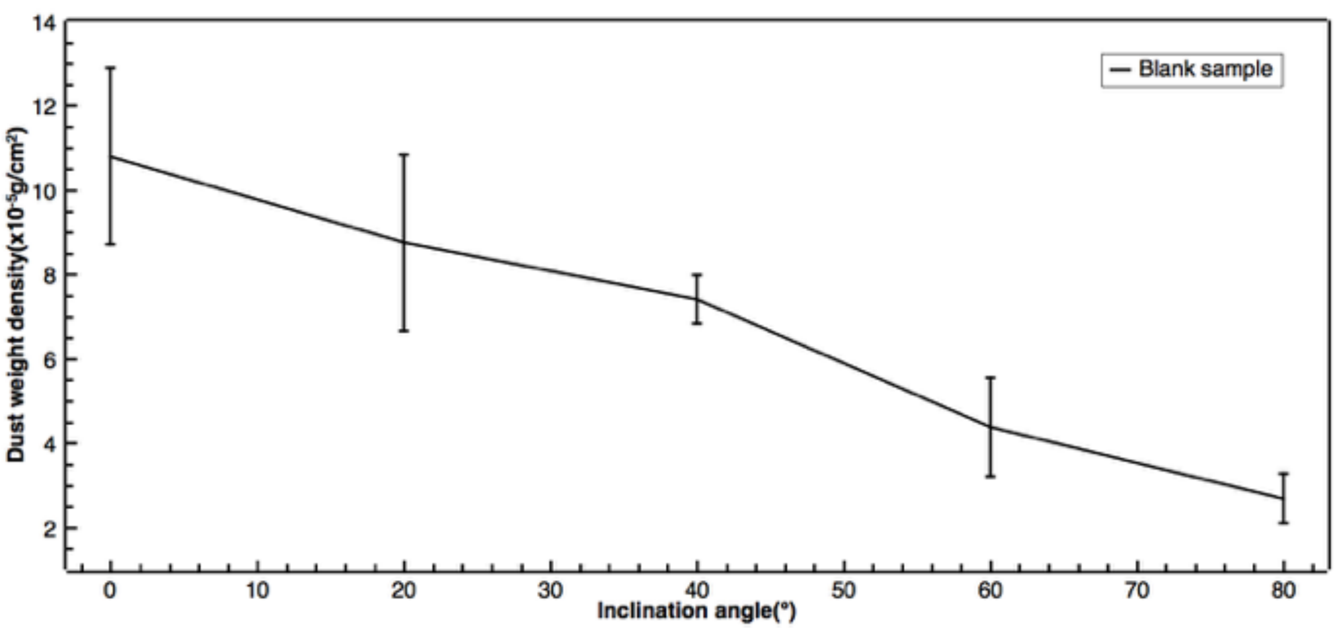

Figure 4-9 Dust weight density vs. inclination angle for blank sample

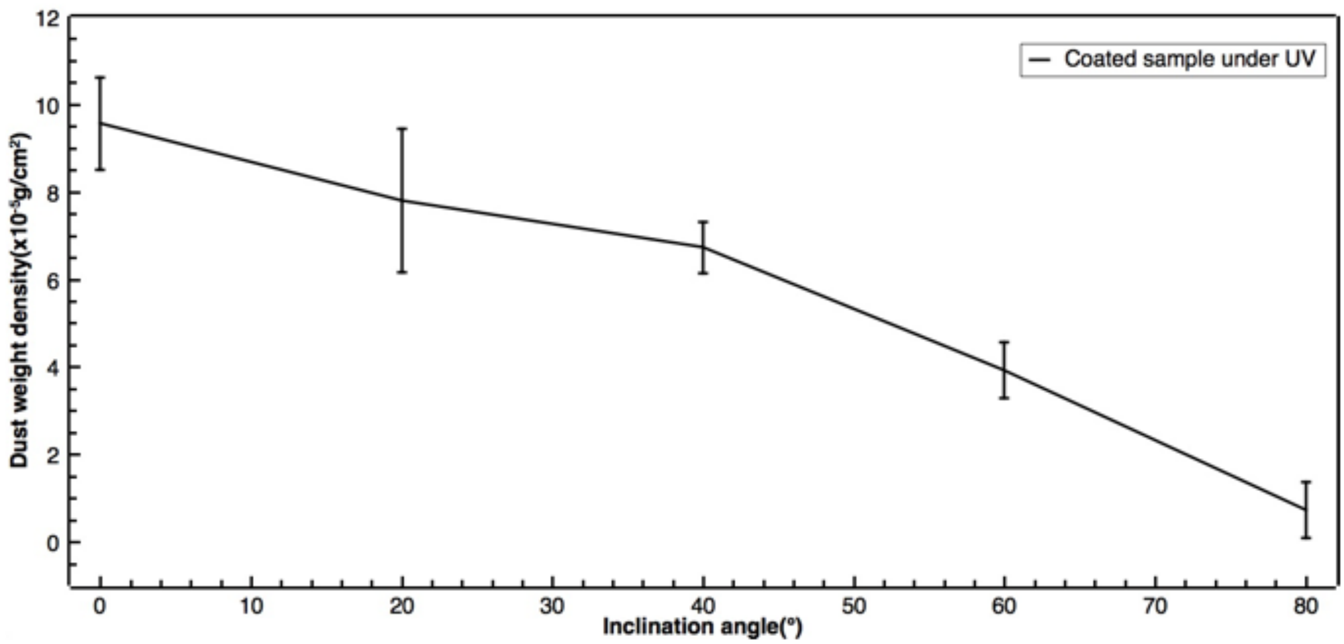

Figure 4-10 Dust weight density vs. inclination angle for coated sample under UV

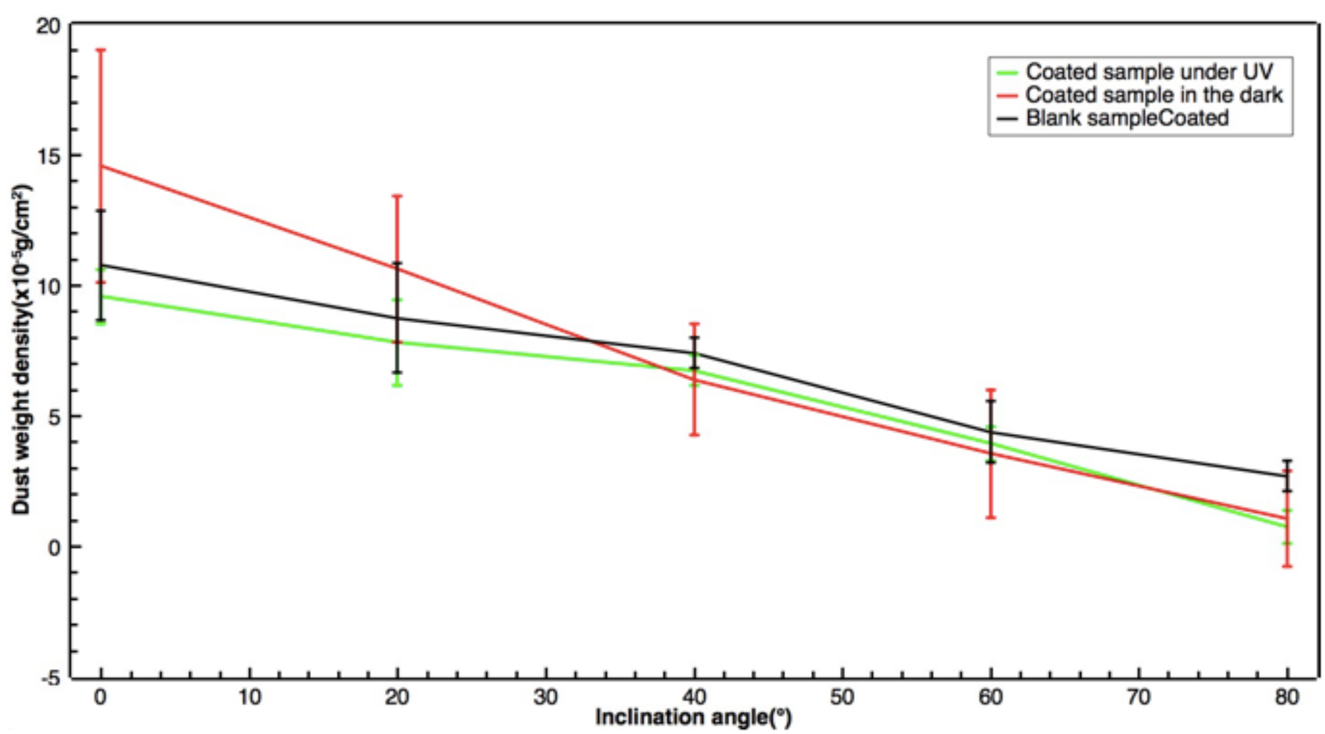

Figure 4-11 Comparison for above three sample

The x axis is inclination angle. The y axis is dust weight density. We can find that as the inclination angle increased, the deposited dust weight decreased, which means the inclination can reduce dust deposition. For every different angle, I simulated three times to make an error bar. The combination result is showed in Figure 4-11.

For Figure 4-11, we can find that for every different angle, three lines' dust density error bar overlaps with each other. Therefore, the result was that PureTi's solution cannot clean dust no matter under dark or under UV light condition. The result matched the contact angle result that non-hydrophobic surface cannot clean dust automatically.

5 CONCLUSION AND FUTURE WORK

5.1 Conclusion

At this experiment, the self-cleaning coating was used to clean organic contamination and impede dust deposition process. The transmittance result, tested by UV-Vis, indicated that self-cleaning coating could block some UV light because several layers coating sample's transmittance was worse. It was found that the transmittance of one-layer sample, coated by spinning coating, was close to the sample coated by spray gun, which means the thickness of this two sample was close.

About IR test, it was found that the stearic acid coating can be cleaned by around 95%, under exposure for 5 minutes. Even the power of light source was higher than the power of sunlight, which is from several hundred to one thousand based on location, season and weather, the cleaning performance was excellent. On the other hand, the transmittance of coated sample reached 90% between 400nm and 1000nm wavelength, which showed an excellent transmittance performance.

However, the self-cleaning coating did not have any influence on dust deposition. From the contact angle part, it was found that this coating did not show hydrophobic property, which means the coating cannot ease dust deposition. And the dust simulation section's result confirmed this assumption that coated sample's and uncoated sample's dust weight overlapped with each other no matter under dark environment or under UV light exposure.

At dust simulation part, it also can be concluded that deposited dust quantity varied with the inclination angle. The transmittance test showed that as the inclination angle increased, the transmittance increased. And the dust deposition weight test also showed the same result that as inclination angle increased, the dust weight density decreased also.

5.2 Future work

The result shows that self-cleaning membrane cannot clean dust. Therefore, in the future work, it is focused on the electric curtain shield to clean dust deposition. This method uses an AC power supply to provide an alternate voltage, which will move the tiny particles in the repulsive force direction. By constant force, the dust can be swept by AC voltage.

This method was firstly used at Mars by NASA[37]. ITO was used as the wire electrodes. ITO's transparency and conductivity property can guarantee that not only the dust can be removed efficiently but also wire electrodes will not block too much light.

5.2.1 Electrode material

At this part, a polymer, with a similar property to ITO, can be selected as the wire electrodes. PEDOT: PSS is a promising candidate from the following analysis.

Conductor	Conductivity
PEDOT: PSS	1000 S/cm
ITO	1300 S/cm
copper	5×10^{5} S/cm.
poly(3-dodecylthiophene) doped with iodine （Polythiophene）	1000 S/cm
Poly(p-phenylene vinylene)	<<10^{-3} S/cm (I2 doped) to 100 S/cm (H_2SO_4-doped)
polyaniline	6.28×10^{-9} S/m (undoped) to 4.60×10^{-5} S/m
Polypyrrole	2 to 100 S/cm

Table 5-1 conductivity comparison of different conductor

Finding a substitute good performance material, which should both be transparent and conductive, is necessary. Table 5-1 is conductivity comparison for ITO, copper and a conductive polymer.

From the table, it can be found that PEDOT: PSS and poly(3-dodecylthiophene)'s conductive property is comparable with ITO's. However, poly(3-dodecylthiophene)'s transparency is not as good as PEDOT: PSS. Comparing PEDOT: PSS with other conductive polymers, we can find that PEDOT: PSS's conductive is much higher than any other polymer.

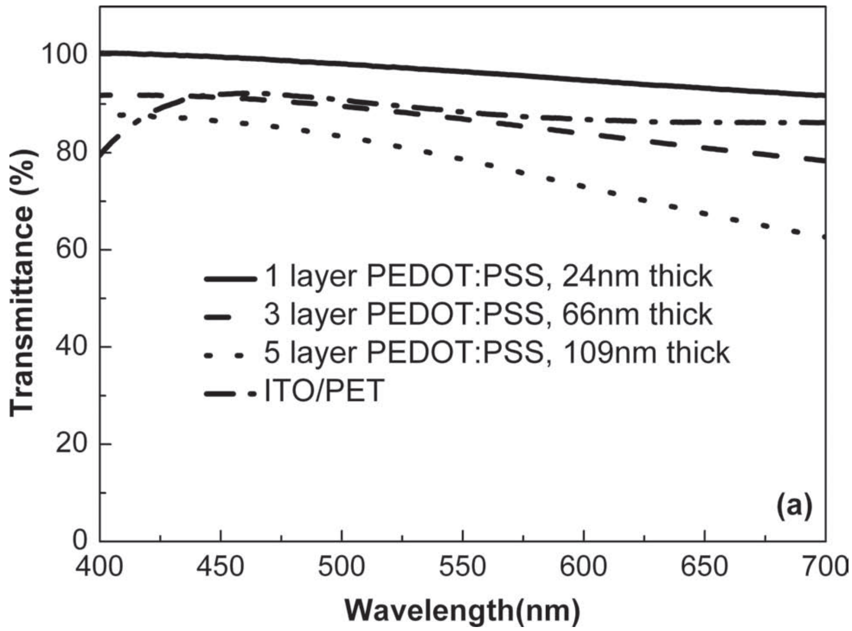

Figure 5-1 [38] Transmittance spectra of PEDOT: PSS films.

Figure 5-1 and Figure 5-2 are the transmittance of PEDOT: PSS, ITO. Take 100nm thick as an example. At 500nm wavelength, ITO and PEDOT: PSS transmittance are both around 80%. The difference is that ITO has a better transmittance when the wavelength is larger than 500nm and PEDOT: PSS is overwhelming at a smaller wavelength.

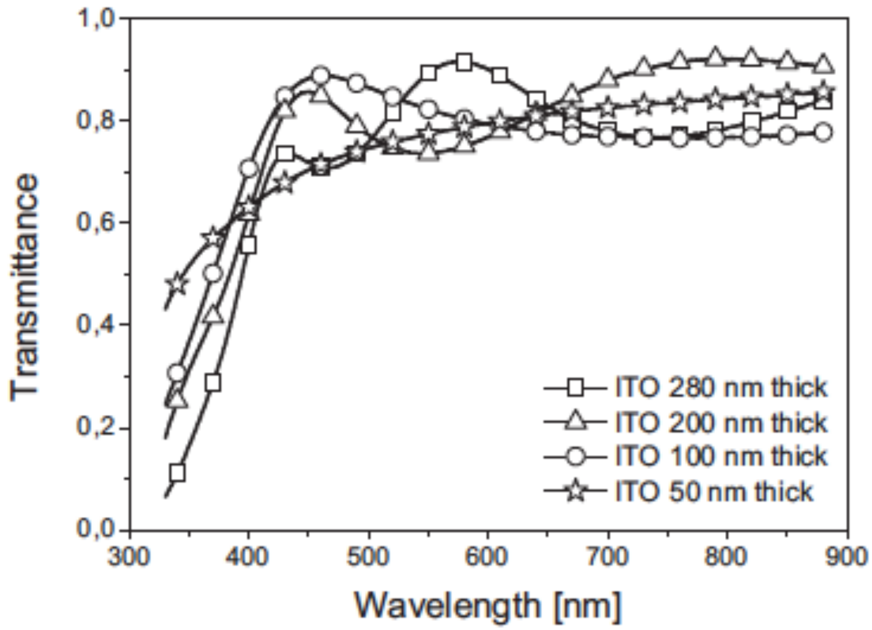

Figure 5-2[39] Results of ITO thin films with different thicknesses measurements: transmittance spectra

Even though metals always own an excellent conductivity, their body can block a large part of irradiation. Therefore, PEDOT: PSS, as a conductive and transparent polymer, is a strong candidate.

5.2.2 Electrodynamic Dust Shield

At this part, single-phase electric shield is a good beginning, due to its simple design and efficient performance[29] . The single-phase excitation produces a standing wave between the electrodes. Standing wave can be considered as a superposition of two traveling waves moving in opposite directions. Dust on the standing-wave curtain is lifted and removed by the electrical force.

Firstly, copper wire will be used as wire electrode. Even though copper wire will block light, it is a good start to measure the voltage and test the efficiency of the method due to its high conductivity. And to decrease the blocking problem, the diameter should be as thin as possible. The frequency of AC power supply should be around 10-50Hz.

After copper wire, we can use PEDOT: PSS as wire electrode. Basically, there's two way to assemble the wire electrode: spinning coating on a covered model, and photolithography[40].

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