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# Effect of photovoltaic panel electric field on the wind speed required for dust removal from the panels

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Methods to remove dust deposits by high-speed airflow have significant potential applications, with optimal design of flow velocity being the core technology. In this paper, we discuss the wind speed required for particle removal from photovoltaic (PV) panels by compressed air by analyzing the force exerted on the dust deposited on inclined photovoltaic panels, which also included different electrification mechanisms of dust while it is in contact with the PV panel. The results show that the effect of the particle charging mechanism in the electric field generated by the PV panel is greatly smaller than the effect of the Van der Waals force and gravity, but the effect of the particle charged by the contact electrification mechanism in the electrostatic field is very pronounced. The wind speed required for dust removal from the PV panel increases linearly with the PV panel electric field, so we suggest that the nighttime, when the PV electric field is relatively small, would be more appropriate time for dust removal. The above results are of great scientific importance for accurately grasping the dust distribution law and for achieving scientific removal of dust on PV panels.

**Keywords:** photovoltaic power generation, dust removal, electrostatic force, required wind speed, contact electrification

**PACS:** 41.20.–q, 41.90.+e, 45.20.da, 88.40.–j **DOI:** 10.1088/1674-1056/acd5c1

## 1. Introduction

With the establishment of the "zero carbon" goal, the construction of a new power system with green and renewable energy as the main body has become an important development direction of the energy industry. Photovoltaic power generation is one of the fastest-developing and most widely used clean and green energy technologies at this stage.[1] The photovoltaic power generation industry has become a key strategic emerging technology industry in many countries. Desertification land is an advantageous area to develop the large-scale and centralized photovoltaic power generation industry, but the special meteorological environment of strong radiation, windy, sandy, and harsh temperature environment has produced many negative effects on the power generation efficiency of photovoltaic (PV) cells.[2,3] The deposition of aerosol particles, such as dust, on photovoltaic panels has an important impact on the effective solar radiation intensity and temperature of photovoltaic cells. Relevant studies have shown that dust deposition will reduce the power generation efficiency of PV panels by about 40%,[4] and there are obvious regional differences.[5,6] Some experimental results show that the surface temperature of PV cells shows a decreasing trend with the accumulation of dust,[7] but different kinds of sediments have great differences in the temperature of photovoltaic cells.[8] For example, ash, soil and cement will cause the temperature of PV cells to rise by about 3 °C, while salt will not cause the temperature of photovoltaic modules to rise significantly. Our research shows that dust accumulation can significantly increase the temperature of PV panels.[9,10] Therefore, dust removal must be timely carried out during PV station operation to ensure efficient power generation of PV panels.

In desertification areas, dust removal for photovoltaic (PV) panels is of great significance for the efficient operation of photovoltaic systems.[11,12] Traditional devices based on dry-brushing, nano-coating, electric curtains, and other methods have not been widely applied due to certain cost problems.[13–15] In recent years, a cooling and dust removal device for PV panels based on compressed air has attracted the attention of researchers, and the unique advantage of this method has been proved.[16] A scientific and comprehensive understanding of the forces acting on dust deposition and the scientific design of airflow velocity will be helpful for the practical design of this type of device.[17–19] As the development of PV technology, the power of a single PV panel continues to increase, and the intensity of the electric field generated around it becomes stronger.[20] The electric field generated by the photovoltaic panel itself has a strong attraction to the deposited particles,[21,22] which is bound to significantly increase the deposition of particles.[23,24] On the other hand, the collision between the deposition particles and the photo-

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voltaic glass panel is also accompanied by the electrification phenomenon, which result in a large amount of electrostatic charges on both the particles and the photovoltaic panel.[20] The electric field generated by the photovoltaic panel will enhance the contact electric charge between objects,[25,26] which will inevitably increase the electrostatic force of the dust on the photovoltaic panel, thus affecting the working efficiency of the dust removal device with compressed air. Therefore, it is of great scientific significance to analyze the critical airflow speed of the dust removal device, which is designed by compressed air, under the action of electric field produced by photovoltaic panels.

Therefore, in this paper, we will discuss the required airflow velocity of a dust removal device with compressed air under the influence of the electric field generated by the PV panel. Compared with the works proposed by previous literatures,[16,27] we introduced the electric field generate by PV panel and the particle electrification mechanism for the first time, so as to calculate the electrostatic force of deposited dust relatively more reasonably.

## 2. Motion criterion of dust on the inclined photovoltaic panels

The forces acting on the dust particles on the surface of the PV panel should include gravity, Van der Waals force, electrostatic force, drag force, lift force, and friction force under the action of wind, and the direction of force is shown in Fig. 1.

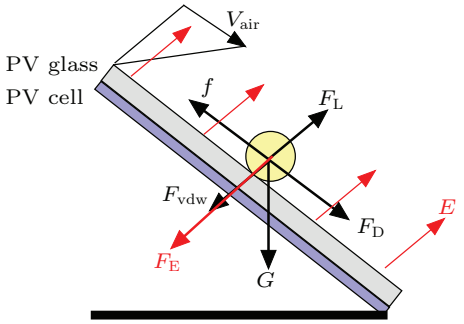



**Fig. 1.** The force analysis of the dust on the photovoltaic panel.

Considering that the air humidity in the desert is usually very low, the capillary force between the dust particles and the glass plate is not considered. Supposed the particle's radius is $R$, the mass density of particle is $\rho$, $g = 9.8$ m/s$^2$. The gravity of particle is

$$G = 4/3\pi R^3 \rho g. \tag{1}$$

The Van der Waals force is[28]

$$F_{vdw} = HR/(12S^2), \tag{2}$$

here $H = 1 \sim 15 \times 10^{-19}$ J, is Hamaker constant. $S = 1 \times 10^{-8}$ m is the minimum distance between the spherical particle and the contact plan.

The electrostatic force is[24]

$$F_E = EQ, \tag{3}$$

where $E$ is the electric field generated by the working photovoltaic panel, the charge $Q = Q_1 + Q_E$, $Q_1$, $Q_E$ represents the electric charge generated by the charging charge of particle in the electric field $E$, and contact electrification charge between particles and photovoltaic panel in the electric field $E$, respectively.

The drag force is[16]

$$F_D = \frac{1}{2} C_D f \rho_{air} \pi R^2 V_m^2 C_u^{-1}, \tag{4}$$

here $f = 1.7009$ is the correction coefficient considering the near-wall effect, $\rho_{air}$ is the air density, $V_m = \Gamma R V_s^2/\nu$ is the average wind speed at the particle center, $\nu = 1.525 \times 10^{-5}$ m$^2$/s represents the aerodynamic viscosity coefficient, but it varies with air temperature, $V_s$ is the shear velocity,[29] $C_D$ is the drag force coefficient, which can be obtained from the following equation:

$$C_D = \begin{cases} \dfrac{24}{R_e}\left(1 + \dfrac{1}{6}R_e^{2/3}\right), & R_e \le 1000, \\ 0.44, & 1000 < R_e \le 2 \times 10^5, \end{cases} \tag{5}$$

$C_u$ is the Cunningham correction factor, which can be obtained from the following equation:

$$C_u = 1 + \frac{\lambda}{R}\left[1.257 + 0.4\exp(-1.1R/\lambda)\right], \tag{6}$$

$\lambda = 6.9 \times 10^{-8}$ m is the mean free path of air molecules. $\Gamma$ is the wall coefficient, which can be set as 1.84.[16,29] $R_e = 2\Gamma(RV_s/\nu)^2$ is the Reynolds. Introduced the parameter $V_m$, it can be simplified as $R_e = 2R/\nu V_m$.

The fluid lift force is[16]

$$F_L = 11.904\rho_{air}\left(V_m R \Gamma^{-1}\right)^2. \tag{7}$$

When the particles on the plate begin moving under the action of compressed air flow, the force acting on the particle should meet following equations:

$$\begin{cases} \text{jump:} \\ F_L \ge F_{vdw} + F_E + G\cos\alpha, \\ \text{slide down:} \\ F_D \ge \mu(F_{vdw} + F_E + G\cos\alpha - F_L) - G\sin\alpha, \\ \text{slide up:} \\ F_D \ge \mu(F_{vdw} + F_E + G\cos\alpha - F_L) + G\sin\alpha, \end{cases} \tag{8}$$

where $R_r$ is the radius of contact area between the particle and the plate, which can be regarded as the roughness of the plate. $\mu$ is the friction coefficient between the plate and the particle.

Thus, the wind speed required for particles moving on the photovoltaic panel can be obtained as

$$\begin{cases} \text{jump:} \\ V_{\mathrm{m}} \geq \left( \dfrac{F_{\mathrm{vdw}} + F_{\mathrm{E}} + G\cos\alpha}{11.904\rho_{\mathrm{air}}} \right)^{0.5} \dfrac{\Gamma}{R}, \\ \text{slide down:} \\ V_{\mathrm{m}} \geq \left[ \dfrac{\mu\left(F_{\mathrm{vdw}} + F_{\mathrm{E}} + G\cos\alpha\right) - G\sin\alpha}{11.904\rho_{\mathrm{air}}\left(\mu + 1.1765\right)} \right]^{0.5} \dfrac{\Gamma}{R}, \\ \text{slide up:} \\ V_{\mathrm{m}} \geq \left[ \dfrac{\mu\left(F_{\mathrm{vdw}} + F_{\mathrm{E}} + G\cos\alpha\right) + G\sin\alpha}{11.904\rho_{\mathrm{air}}\left(\mu + 1.1765\right)} \right]^{0.5} \dfrac{\Gamma}{R}. \end{cases} \tag{9}$$

Obviously, if we can calculate the electrostatic force accurately, we can obtain the critical wind speed for particles moving under the action of compressed air flow and the electric field of photovoltaic panel.

## 3. Friction coefficient between dust particles and photovoltaic glass

In order to more accurately characterize the friction force of a particle deposited on the photovoltaic glass panel, we measured the friction coefficient of a small patch of PV glass moving on a larger dusty PV glass panel based on the traction method. Figure 2 shows the experimental schematic diagram and the associated experimental equipment. The size of the small photovoltaic glass panel used in the experiment is 13.5 cm×13.5 cm, with a mass of $M$. It was placed on the table, and an empty cup, which had been weighed, was selected and attached by a string to the small PV glass plates, in the centre of which was placed a fixed pulley. Some dust is poured slowly and evenly into the empty cup until the small PV glass begins to move. The electronic dynamometer was used to weigh the dust particles in the cup, labeled as $m$, and the friction coefficient $\mu$ between the particles and the plate was calculated using the following equations:

$$\mu = \frac{mg}{Mg} = \frac{m}{M}. \tag{10}$$

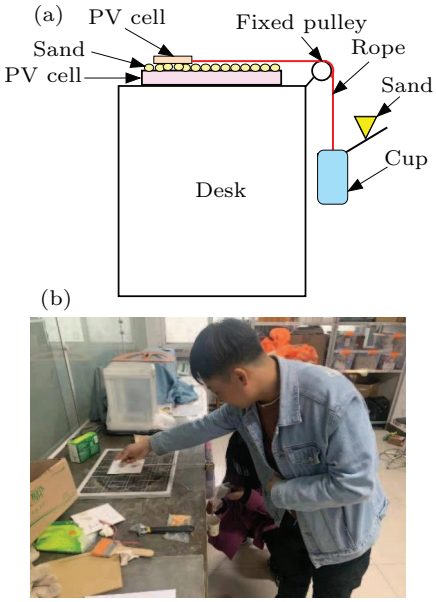



**Fig. 2.** Experimental principle and equipment: (a) schematic diagram of the experiment, (b) experiment photo.

The dust on the larger PV glass was screened with different aperture sizes, and the particle sizes were distributed over a limited range to reduce experimental errors caused by the rolling of particles on the photovoltaic glass. Each experiment was repeated three times and then the arithmetic mean was taken. The experimental results are shown in Table 1. According to the data in the table, the friction coefficient between the dust particles and the photovoltaic glass plate is likely to between 0.7–0.8, except in the two sets of data where the deposition particle size is between 0.125 mm and 0.18 mm. We repeated the experiment and found no significant improvement. The deposition of different particle sizes on the bottom glass plate has relatively little effect on the results, but the deposition amount will have a certain degree of effect on the measurements. In the calculation presented in the following section, the friction coefficient was chosen to be 0.8.

**Table 1.** Friction coefficient of particles with different sizes (three kinds of deposition densities).

| Particle size (mm) | ≤ 0.1 | 0.1–0.125 | 0.125–0.154 | 0.154–0.18 | 0.18–0.28 | ≥ 0.28 |
|---|---|---|---|---|---|---|
| 0.1646 (g/cm$^2$) | 0.7872 | 0.7279 | 0.6528 | 0.5752 | 0.6815 | 0.6865 |
| 0.2195 (g/cm$^2$) | 0.8013 | 0.7987 | 0.6655 | 0.6330 | 0.7433 | 0.8630 |
| 0.3124 (g/cm$^2$) | 0.8223 | 0.8014 | 0.6936 | 0.7122 | 0.8214 | 0.8409 |

## 4. Particle electrification mechanism

### 4.1. Charging mechanism in electrostatic field

Due to the existence of electric current, an electric field will be generated around it.[30] Therefore, the PV panel current can generate electric field $E$ around it. Assume that there is a spherical dust particle with radius $R$, resting on the plate. Under the action of the electric field, the saturation charge of the ball can be calculated by the following equation:[31]

$$Q = K\pi\varepsilon_0 E R^2, \tag{11}$$

here $K$ can be determined from Eq. (12),

$$K = \begin{cases} 6.56, & \text{conductor}, \\ \dfrac{6.6\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{r}} + 2}, & \text{dielectric}, \end{cases} \tag{12}$$

where $\varepsilon_0$ is the vacuum dielectric constant, and the value is $8.85\times10^{-12}$ C·V$^{-1}$·m$^{-1}$. $\varepsilon_r$ is the relative permittivity of the sphere.

The permittivity of dust particles can be obtained by the fitting function established by Sharif *et al.*,[32]

$$\varepsilon_r = \varepsilon_d + 0.04H_0 - 7.78\times10^{-4}H_0^2 + 5.56\times10^{-6}H_0^3, \quad (13)$$

where $H_0$ represents the water content of dust particles, $\varepsilon_d$ is the relative dielectric constant of dry dust particles, and in this paper we set it as 4.2. Considering that it takes a certain time for particles to charging, the final charge on particles can be expressed as follows:[31]

$$Q_{(t)} = Q_s\{1-\exp[-t/(\rho_s\varepsilon_r\varepsilon_0)]\}, \quad (14)$$

where $\rho_s = 4/3\times n\times10^{8-0.44n}$, $n = 0.057 + 23.5H_0 - 50.7H_0^2 + 62.9H_0^3$. After obtaining the charge on the deposited particle, and set the mass of particle is $M_s$, the charge–mass ratio can be calculated with the equation $q_m = Q/M_s$.

The effect of particle parameters and the strength of the external electric field on the particle charge will be discussed below.

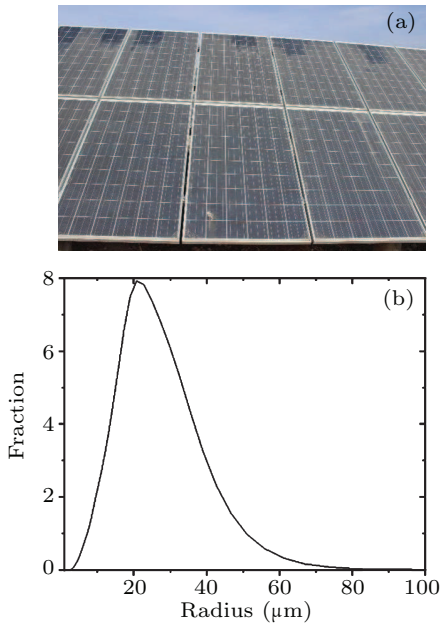



**Fig. 3.** Dust deposition on the photovoltaic panel and its size distribution: (a) natural dust deposition on photovoltaic panels, (b) size distribution function of deposited dust.

Dust samples were collected from a desert photovoltaic power station in Ningxia province in China, and the particle size distribution function was measured, the results shown in Fig. 3. From them we found, $D_{10} = 9.8$ μm, $D_{50} = 20.09$ μm, $D_{90} = 35.13$ μm, and about 99% of the particle size is less than 44.66 μm. Therefore, the particle radius in this section is chosen to be 20 μm, the relative dielectric constant of dry particles is 4.2, the applied electric field is 2 kV/m,[22] and the particle humidity is 0.2. In the following simulation calculations, the above parameters are kept unchanged unless specified otherwise.

In Fig. 4, we discussed the variation of charge amount of particles with different particle sizes and applied electric field. It can be seen from the figure that as the contact time increase, the charge of particle with different sizes increases, and the charge saturates after 2.5 ms. At the same time, as the particle size increases, the charge-to-mass ratio of the particle decreases significantly. This is because the charge of a particle is proportional to the second power of its radius, while the particle mass is proportional to the third power of its radius, thus the charge-to-mass ratio of a particle is inversely proportional to its radius. When an electric field is applied, the charging process of the deposited particles quickly saturates, and the charge on the particles increases linearly with the increase of the applied electric field.

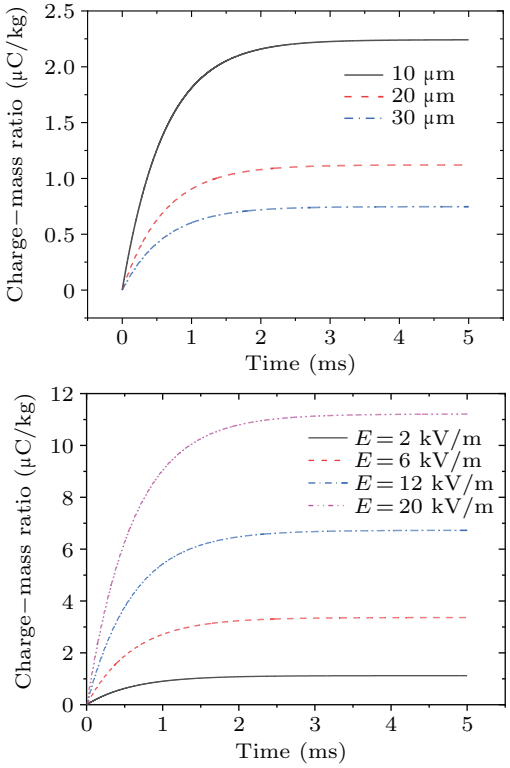



**Fig. 4.** Effect of the particle radius and applied electric field on the amount of charge.

We now discuss the wind speed required for a particle to jump from a PV panel under the influence of electric field generated by PV panel. The results are shown in Fig. 5. It can be seen from them that the charge–mass ratio of the particle increase linearly as the electric field generated by the PV panel increases, but the larger the particle size, the smaller the charge-to-mass ratio of the particle. However, as the electric field of the PV panel increases, the wind speed required for particle take-off remains approximately constant, but from Fig. 6 we can see that it decrease approximately exponentially as the particle size increases. This is mainly because the elec-

trostatic force on the particle is much smaller than the van der Waals force and gravity, but increases with the particle size.

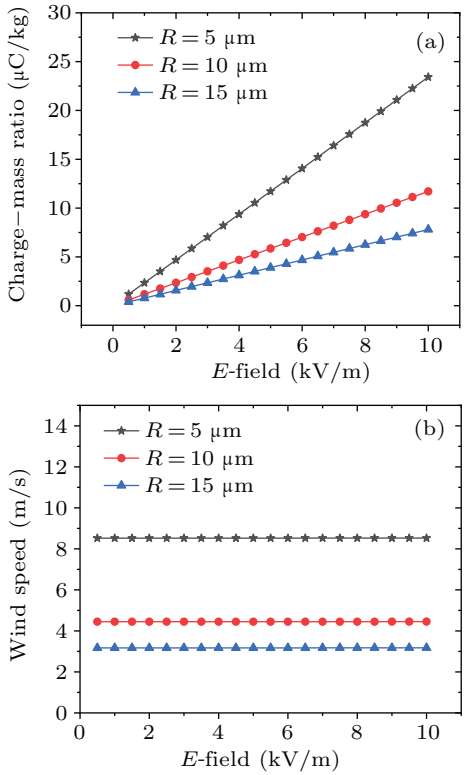



**Fig. 5.** Effect of the electric field on the particle charge–mass ratio (a) and its take-off wind speed (b).

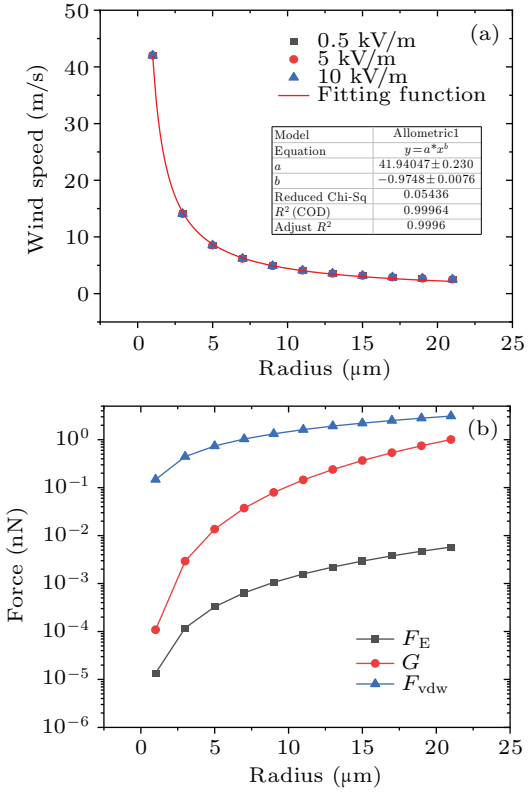



**Fig. 6.** Effect of particle size on critical wind speed of particle motion: (a) required wind speed varies with particle size, (b) action force on particle.

In Fig. 7, we compare the wind speed required for particles to taking-off or to slide. The figure shows that the required wind speed decreases as a power function with the particle size increases, mainly because the van der Waals force decreases significantly as the particle size increases, while the fluid lift force synchronized increases. However, we also can find that the wind speed required by the particles to slide down along the plate is much smaller than that of particles take-off, which is mainly due to the fact that the force to be overcome by the particles to jump is larger than that by gliding. At the same time, for particles smaller than 3 microns, the wind speed required for upward or downward sliding is essentially the same, while the required wind speed gradually decreases as the particle size increases, but the difference between them gradually increases.

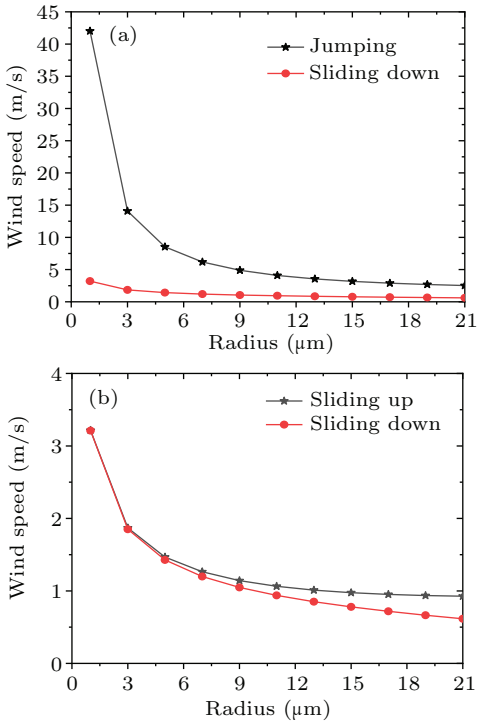



**Fig. 7.** Comparison of the required wind speeds for particles taking off or sliding.

### 4.2. Contact electrification of particles under electric field

In this section we quote the method proposed by Xie *et al.*[20] Assuming that the particle radius is $R_1$, $r_1$, respectively, and $D_1 = 2R_1$, $D_2 = 2r_1$, the corresponding mass is $m_1$, $m_2$, the elastic modulus and Poisson's ratio of the particle are $E_i$, $\nu_i$, the relative velocity during collision is $v_r$ then the contact area between the two particles during the collision contact can be obtained from the following equation:[33]

$$A_1 = 0.5\pi D_1^2\left(1-\sqrt{1-4D_2\delta_{\max}^1/[D_1(D_1+D_2)]}\right), \quad (15)$$

$$A_2 = 0.5\pi D_2^2\left(1-\sqrt{1-4D_1\delta_{\max}/[D_2(D_1+D_2)]}\right). \quad (16)$$

It is assumed that the colliding process between two particles is elastic loading and elastic–plastic unloading. The parameters involved in the above equation can be obtained by the

method proposed by Zhou[34] and can be expressed as follows:

$$\delta_{\max} = \left(\frac{5}{4}\frac{M}{K}v_{\mathrm{r}}^2\right)^{0.4}, \quad R = \frac{r_1 R_1}{r_1 + R_1}, \quad M = \frac{m_1 m_2}{m_1 + m_2},$$
$$E = \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{-1}, \quad K = \frac{4}{3}ER^{0.5}.$$

Assume that the initial surface charge density is $\rho$, $P_{\mathrm{D}}$ is the exchange probability of charged ions on the particle surface, which is related to the number of collisions.[35] In this paper, we consider single collisions of particles, and the value of $P_{\mathrm{D}}$ is 0.5. Then, after a single collision, the particle charge can be expressed as follows:[33]

$$Q_1 = \rho P_{\mathrm{D}}(1 - P_{\mathrm{D}})(A_2 - A_1). \tag{17}$$

Assuming that particles are uniformly charged, the charge after the particles collide with the plate under the action of the electric field is[20]

$$\Delta q_{ij} = \gamma_1 E r_i^2 \cos\theta + (\omega - 1)\, Q_j + \omega Q_i, \tag{18}$$

Here $E$ is the environmental electric field, $r_i$ is the radius of the $i$-th particle, $\theta$ is the angle between the line of particle center and electric field, $Q_i$, $Q_j$ are respectively the charge carried by the $i$-th and $j$-th particles before the collision, which can also be called the original charge of the particles. $\omega$ is the transfer ratio of the particle's original charge. $\gamma_1$ is a function of the particle size ratio. Supposed $\alpha = r/R$, the values of $\gamma_1$ and $\omega$ can be obtained numerically, which is shown in Table 2. Wang *et al.*[26] and Li *et al.*[20] have discussed in detail the variation rule of the contact electric charge of charged particles under the action of an external electric field, and they have shown that the electric field of the PV panel plays an crucial role in the charge of the deposited particle.

**Table 2.** Values of $\gamma_1$ and $\omega$.

| $\alpha$ | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
|---|---|---|---|---|---|---|
| $\gamma_1$ | 4.93 | 3.9 | 3.1 | 2.55 | 2.06 | 1.64 |
| $\omega$ | 1 | 0.948 | 0.838 | 0.714 | 0.6 | 0.5 |

In the following, we will discuss the effect of the electric field generated by the working photovoltaic panel on the variation law of the particle force and the wind speed required for particle to slide. The results are shown in Fig. 8 and we have set $E = 1$ kV/m. As can be seen in Fig. 8, the wind speeds required for the particle to slide up or down, all decrease as a power function of the particle size, but the difference between them increases approximately linearly. This is mainly because the electrostatic force on the particle gradually increases with the particle size, and the friction force increases accordingly. When the particle size is larger than 7 μm, the electrostatic force may be larger than the van der Waals force. Moreover, from Eq. (17), we know that the charge on the particle is proportional to the strength of the applied electric field, so that the electrostatic force on the particle will inevitably increase significantly as the electric field generated by the PV panel increases.

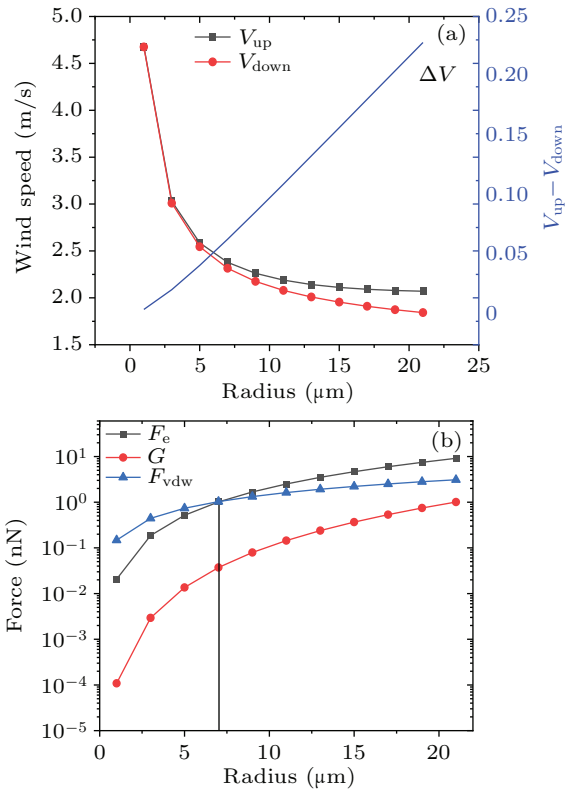



**Fig. 8.** Variation of required wind speed *versus* particle size and the force on particles ($E = 1$ kV/m).

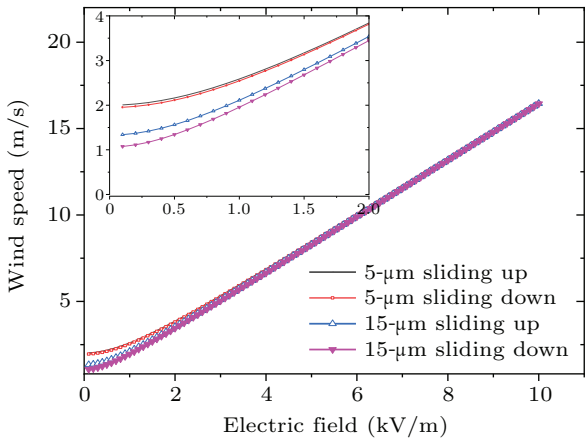



**Fig. 9.** Wind speed required for particle sliding under different electric field strengths.

Finally we discussed the variation of the required wind velocity for particles sliding along different directions under different electric fields in Fig. 9. From it we can see that the wind speed required for the particles to slide is different and varies with the particle size, the direction of motion, and the electric field strength when the electric field is smaller than

3 kV/m. However, when the electric field exceeds the threshold value, the wind speed required for the particle to slide up or down is the same and keeps on increasing. The electric field cause an increase in the detachment threshold wind for the dust deposition, which can be confirmed by the experimental results proposed by Holstein–Rathlou *et al.*[36] It is easy to find that when the electric field goes to zero, the wind speed required for a 5-micron particle to slide is less than 2 m/s, which is similar to the experimental results presented by Ibrahim *et al.*[17] Therefore, when using compressed air to remove dust from PV panels, it is necessary to reduce the electric field of the PV panels first.

## 5. Discussion

Micro-particle detachment or removal from material surfaces is an important subject with widely applications.[17] Since it can also be used to cool the PV panel, the dust removal technology using compressed air for the photovoltaic panel has attracted the attention of numerous scholars.[37] However, few experiments have investigated the effect of the electric field generated by the PV panels, which would significantly underestimate the particle adhesion force.[20] Just as shown in Fig. 9, when the electric field is reduced to 2 kV/m from 10 kV/m, the required wind speed is reduced to 3 m/s from 16.5 kV/m, and when it close to 0 kV/m, the required wind speed is less than 2 m/s, which is extremely small for compressed air. This is extremely beneficial to removal the deposition particles. Of course, the principle of dust removal by compressed air is based on the fact that the drag force under the action of wind is greater than the adhesion force of particles, cemented particles that adhere strongly to PV panels by daily repeated humid/dry cycles are difficult to remove, unless the income wind is large enough, or the cementing layer breaking and splashing under the impact of other particles. Therefore it is necessary to set a special operation scheme for compressed air dust removal to prevent the formation of cementing layer. In addition, the model in this paper does not take into account the effect of boundary layer and the surface macro-roughness,[38] which would overestimate the effect of fluid force. The size distribution and shape of dust also needs to be considered, because they all affect the fluid force of the particles. In the future, we can try to analysis it based on the Monte Carlo simulation method.

## 6. Conclusion

We analyzed the force situation of the dust on the PV panels, and firstly designed an experiment to measure the friction coefficient between dust deposition and photovoltaic glass. The friction coefficient was found to be between 0.6 and 0.9. Based on these results, we discussed the wind speed required for dust particles to slide along the panel in the presence of PV panel electric field, and its variation law with particle size and photovoltaic panel electric field. The results show that the flow velocity decreases as a power function with increasing particle size, but increases approximately linearly with increasing electric field strength. These results indicate that in the design of dust removal of photovoltaic panels based on compressed air, it is necessary to first reduce the electric field of photovoltaic panels (that is, dust removal can be carried out at night when photovoltaic panels are barely not working), which will be beneficial to improve the dust removal effect.

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## References

[1] Parida B, Iniyan S and Goic R 2011 *Renew. Sust. Energy Rev.* **15** 1625
[2] Song Z, Liu J and Yang H 2021 *Appl. Energy* **298** 117247
[3] Sun C, Zou Y, Qin C, Zhang B and Wu X 2022 *Adv. Compos. Hybrid Ma.*
[4] Said S A M 1990 *Appl Energ* **37** 73
[5] Vivar M, Herrero R, Antón I, Martínez-Moreno F, Moretón R, Sala G, Blakers A W and Smeltink J 2010 *Sol. Energy* **84** 1327
[6] Tanesab J, Parlevliet D, Whale J, Urmee T and Pryor T 2015 *Sol. Energy* **120** 147
[7] Zhao M, Wang S, Zhang Z, Zhang D and Wu L 2020 *Acta Energiae Solar Sinics* **41** (in Chinese)
[8] Abderrezek M and Fathi M 2017 *Sol. Energy* **142** 308
[9] Xu L, Li S, Jiang J, Liu T, Wu H, Wang J and Li X 2020 *Sol. Energy* **199** 491
[10] Li X, Liu T, Wang J, Xu L and Zhang Z 2020 *J. Quant. Spectrosc. Ra.* **246** 106921
[11] Nahar Myyas R E, Al-Dabbasa M, Tostado-Véliz M and Jurado F 2022 *Sol. Energy* **237** 19
[12] Yilbas B S, Abubakar A A, Al-Qahtani H, Mohammed A S and Al-Sharafi A 2021 *Sol. Energy* **225** 708
[13] Derakhshandeh J F, Alluqman R, Mohammad S, AlHussain H, Al-Hendi G, AlEid D and Ahmad Z 2021 *Sustain. Energy Techn.* **47** 101518
[14] Salamah T, Ramahi A, Alamara K, Juaidi A, Abdallah R, Abdelkareem M A, Amer E C and Olabi A G 2022 *Sci. Total Environ.* **827** 154050
[15] Kazem H A, Chaichan M T, Al-Waeli A H A and Sopian K 2020 *J. Clean. Prod.* **276** 123187
[16] Li D, King M, Dooner M, Guo S and Wang J 2021 *Sol. Energy* **221** 433
[17] Ibrahim A H, Dunn P F and Brach R M 2003 *J. Aerosol Sci.* **34** 765
[18] Ibrahim A H, Dunn P F and Brach R M 2004 *J. Aerosol Sci.* **35** 805
[19] Kawamoto H, Tanabe J and Kobayashi Y 2021 *J. Electrostat.* **113** 103618
[20] Li X, Wang J and Su G 2021 *Chin. Phys. B* **30** 104101
[21] Jiang C S, Moutinho H R, To B, Xiao C, Perkins C, Muller M, Al-Jassim M M and Simpson L J 2019 *IEEE J. Photovolt.* **9** 1121

[22] Jiang C S, Moutinho H R, To B, Xiao C, Simpson L J and Al-Jassim M M 2020 *Sol. Energy Mater. Sol. Cells* **204** 110206

[23] Liu X, Yue S, Lu L and Li J 2019 *Energies* **12** 4550

[24] Liu X, Yue S, Li J and Lu L 2020 *Sci. Total Environ.* **754** 142241

[25] Zhang Y, Pahtz T, Liu Y, Wang X, Zhang R, Shen Y, Ji R and Cai B 2015 *Phys. Rev. X* **5** 011002

[26] Wang J and Li X 2020 *J. Deser. Res.* **40** 23 (in Chinese)

[27] Du X Q, Liu E X, Wu C Y, Xu N N and Yuan B 2018 *China Mechanical Engineering* **29** 2959 (in Chinese)

[28] Mittal K L and Jaiswal R 2015 *Particle Adhesion and Removal* (Chichester: John Wiley) pp. 27–48

[29] Jiang Y, Lu L, Ferro A R and Ahmadi G 2018 *Sol. Energy* **159** 1031

[30] Hernandes J A, Assis A K T, Sidharth B G, Honsell F, Mansutti O, Sreenivasan K and De Angelis A 2008 *AIP Conf. Proc.* 236–239

[31] Wu Y, Castle G S P, Inculet I I, Petigny S and Swei G 2003 *Powder Technol.* **135–136** 59

[32] Sharif S M 2015 *PIER* **43** 9

[33] Xie L, Li G, Bao N and Zhou J N 2013 *J. Appl. Phys.* **113** 184908

[34] Zhou Y H 2011 *Theo. Appl. Mech. Lett.* **1** 041006

[35] Yu H X, Mu L A and Xie L 2017 *J. Electrostat.* **90** 113

[36] von Holstein-Rathlou C, Merrison J P, Brædstrup C F and Nørnberg P 2012 *Icarus* **220** 1

[37] King M, Li D, Dooner M, Ghosh S, Roy J N, Chakraborty C and Wang J 2021 *Energies* **14** 4072

[38] Eisner A D 2016 *J. Aerosol. Sci.* **102** 16