The mechanism study of dust removal with transparent interdigitated electrodes

Wu Guangming\textsuperscript{a}, Li Dan\textsuperscript{b}, Xing Guangjian\textsuperscript{a}, and Yin Tianlan\textsuperscript{b}

\textsuperscript{a}Beijing Institute of Petrochemical Technology, Beijing, China; \textsuperscript{b}Beijing University of Chemical Technology, Beijing, China

ABSTRACT

Due to the impact of dust on the solar panels cannot be ignored, dust removal technique with electric curtain received extensive attention and research for its own advantages. The mechanism of dust removal with electrical curtain was proposed based on the structure of electric curtain, the force of the dust in the standing waves of electric curtain, the distribution of electric field intensity in the electrode overhead, the physical model calculations of the electrode electric field and the analysis of electrodes breakdown voltage. The work has great significance to the development of dust removal with electric curtain technology.

1. Introduction

In currently, solar panels are the most widely used power generation equipment that converts light energy into electrical energy. When the outdoor solar panels receiving sunshine, they can adsorb amounts of dust in the air, and dust can also land on solar panels in natural surroundings, which will seriously affect the solar panels’ absorptivity of sunshine, then gradually reduce their conversion efficiency. At the same time, the dust will seriously affect not only the use of solar energy, but also the life and precision of observation instruments [1–3]. So the dust removal from the surface of solar panels and all kinds of optical instruments is particularly important [4].

In all kinds of dust removal technologies [5], electric curtain is high-profile for its advantages such as non-contact, no injury to solar panels, high efficiency and clean, so it has become a hot spot in dust removal research [6, 7]. Electric curtain dust removal was put forward by Tatom for the first time in 1967. The movement of dust particles in the electric curtain was researched by Masuda et al. The application of electric curtain was explored by Schmidin and Melcher [8–10]. The influence of the electrostatic force and dielectrophoresis force in electric curtain on dust removal
was studied by Calle C I and others, and the electric curtain were applied to space exploration [11]. J. S. Marshall analyzed the movement of dust under the action in travelling wave electric curtain and standing wave electric curtain, and provided a systematic theoretical basis for the application of electric curtain dust removal technology [10, 12].

Now there have been many studies of the travelling wave electric curtain, however the dust removal efficiency and mechanism of standing wave electric curtain are relatively few. So on the basis of the literatures [13], the dust removal mechanism of standing wave electric curtain was studied systematically, and the structure of electric curtain, the force of dust in the standing wave electric curtain, the electric field intensity distribution over the electrode, the physical model calculation of the electric field and the breakdown voltage of the electrode had been analyzed. That has a certain reference effect to the electric curtain dust removal technology.

2. The basic structure

Figure 1 is the diagrammatic drawing of the homemade interdigitated electrodes. The peripheral black line in the Figure 1 is the edge of glass substrate. The blue and red horizontal lines are interdigitated electrodes. The red and blue squares at the bottom of Figure 1 are the power supply interfaces. The two vertical lines are the electrode edges. The interdigitated electrodes are rectangular, the length of electrodes is $\alpha$, electrode width is $\beta$, and the distance between adjacent electrodes is $\gamma$.

3. The analysis of dust removal mechanism

3.1. The force analysis of dust

Figure 2 shows the polarization force analysis of the dust in the alternating electric field. Figure 2A shows that after polarization, the dust appears polarization charge

![Figure 1. Interdigitated electrodes.](image-url)
Figure 2. Analysis of dust removal mechanism in alternating electric field.

that contrary to the electrode along the both ends of the electric field lines when the left side is anode and the right side is cathode. After the electrode exchange (such as Figure 2B, left side is cathode and the right side is anode), there isn’t enough time for the polarization charge to change its direction, then the dust particles will leave the plate under the instantaneous action of the electric field. The upward force should be greater than gravity of dust particles.

Figure 3 shows the electric field force analysis of the dust in the position of a and b. In the position a, after the electric field changes, the electric field force acting on dust particles must overcome not only the gravity of dust particles, but also the adhesive power between the dust particles and the plates. In position b, after the electric field changes, the factors of the stable equilibrium turning into unstable equilibrium and vibration can make the force on dust increase, and if there is no other disturbance, it is difficult to remove the dust. But the film thickness of our electrode is 200 nm, and the size of dust is more than 1000 nm, so dust removal will be easier.

Figure 4 shows the enlarged image of location a in Figure 3. According to the theory of charged conductor, charges distribute at the position with minimum curvature radius, which are the both sides of the plate. For example, the charges in the position c are more, but few in position d. Near the surface of the plate, there is a strong field strength in position c, but a weak field strength in position d, and the dust removal ability is also poor in position d, which has been proved with experiments, as shown in Figure 5.

Figure 3. Electric field force analysis of dust.
3.2. Electric field intensity analysis over the electrode

The distribution of electric field intensity over two interdigitated electrodes has been analyzed by using of ANSYS software when they were applied an alternating current, the result is shown in Figure 6. The electrode width is 0.5 mm, and the electrode spacing is 1.3 mm. The figure shows that in the vertical direction, the higher distance from the electric curtain surface, the weaker the electric field strength is. In horizontal direction, the electric field strength changes in cycles, and the maximum value appears on both sides of the electrode edge, which is caused by the mutation of the electric potential. The change is consistent with our theoretical analysis and experimental verification.

3.3. Physical model analysis of electric field of the interdigitated electrodes

The parameters such as electric field intensity and the force on dust were studied through establishing the physical model of dust in the electric field of interdigitated electrodes. Our model was established based on the following four conditions:
1. Considering the electrode width is small, we choose the cylindrical infinite length charged conductor as electrode, and the width of the electrode is equal to the cylinder diameter. The charge per unit length is $\lambda$.

2. The distance between the electrodes is $L$, as the center-to-center spacing of two parallel infinite long cylinders.

3. After the polarization along the electric field lines, dust is equivalent to the electric dipole, then $p = ql$, and in anywhere, the angle with the $x$ axis is $\alpha$.

4. Considering the periodic distribution of the negative and positive interdigitated electrodes, and the small influence of adjacent electrodes, we only consider the influence of nearest positive and negative electrodes for the simple calculation.

According to Figure 7, we can calculate that the electric field intensities along the direction of $x$ axis and $y$ axis of the electric dipole in position $P(x, y)$ are respectively as followings:

$$E_x = \frac{\lambda}{2\pi \varepsilon_0} \left[ \frac{x}{x^2 + y^2} + \frac{L - x}{(L - x)^2 - y^2} \right]$$

$$E_y = \frac{\lambda}{2\pi \varepsilon_0} \left[ \frac{y}{x^2 + y^2} - \frac{y}{(L - x)^2 - y^2} \right]$$

According to the formula $F = Eq$, we can calculate from Figure 8 that under the effect of electric field, the electric field force component of the electric dipole along the $x$ axis and $y$ axis are respectively as followings:

$$F_x = \frac{q\lambda}{2\pi \varepsilon_0} \left[ \frac{x}{x^2 + y^2} + \frac{L - x}{(L - x)^2 - y^2} - \frac{x + l \cos \theta}{(x + l \cos \theta)^2 + (y + l \sin \theta)^2} \right.$$

$$- \left. \frac{L - x - l \cos \theta}{(L - x - l \cos \theta)^2 - (y + l \sin \theta)^2} \right]$$
**Figure 8.** Force analysis of electric dipole in the electric field.

\[
F_y = \frac{q\lambda}{2\pi\varepsilon_0} \left[ \frac{y}{x^2 + y^2} - \frac{y}{(L - x)^2 - y^2} - \frac{y + l \sin \theta}{(x + l \cos \theta)^2 + (y + l \sin \theta)^2} \right]
+ \frac{y + l \sin \theta}{(L - x - l \cos \theta)^2 - (y + l \sin \theta)^2}
\]

3.4 The voltage breakdown analysis of electrode

If it is approximately considered that between the two electrodes there is a uniform electric field \(E\), then \(U = Ed\). \(U\) is the electrode voltage and \(d\) is the electrode width. It is known that the breakdown voltage of air is \(E_0 = 2 \times 10^6\) v/m, when \(d = 0.8 \times 10^{-3}\) m, the corresponding breakdown voltage is \(U_0 = 1.6 \times 10^3\) v. It is basically consistent with experimental conditions. Thus we get a principle between the maximum voltage and the width of electrode, that is \(U = Ed\).

4. Conclusions

With the dust removal technology of electric curtain, the dust appears polarization charge that contrary to the electrode particles after polarization in the electric field, and when the electrode exchange, there isn’t enough time for polarization charge to change, and then the dust particles will leave the plate under the instantaneous action of the electric field. In different position of the electrode, there is different electric field intensity, and then the electric field force on the dust is different. Generally speaking, in the vertical direction, the higher distance from the electric curtain surface, the weaker the electric field strength is. In horizontal direction, the electric field strength changes in cycles, and the maximum value appears on both sides of the electrode edge. Through the establishment of physical model, we get the theoretical calculation formula of the electric field force on the dust in the electric curtain, which shows the theoretical guidance and support for the electric curtain dust removal experiment.
References

1. Panmao Zhai, and Xiaoyan Li. The climatic conditions of sand and dust weather in northern China[J]. Geography Journal 58(S1), 125–131 (2003).
2. The United States developed automatic dust removal solar panels[J]. Invention & Innovation 10, 33 (2010).
3. Zhibin Sun, Xuefeng Liu, and Chao Wang. The effect of alternating electric field to remove dielectric particles[J]. Chinese Journal of Space Science 31(6), 808–813 (2011).
4. Guanqing Liu, Shuiqing Li, and Guanqing Liu. To simulate motion features of Mars in travelling wave electric curtain[J]. Journal of Engineering 32(12), 2073–2075 (2011).
5. Guangming Wu, Dan Li, and Jianxing Yu. Further Study of Electric Dust Removal with Transparent Fork Electrodes[J]. American Journal of Analytical Chemistry 6, 196–201 (2015).
6. Yafei Yuan, Min Liu, and Xiangchun Bai. The current research status of electric curtain dust removal technology[J]. Spacecraft Engineering 19(5), 89–94 (2010).
7. H. Kawamoto. Electrostatic and electromagnetic cleaning of lunar dust adhered to spacesuits[C]. Annual Meeting of LEAG. Houston: Lunar and Planetary Institute, 4004 (2009).
8. D. Qian, J. S. Marshall, and J. Frolik. Control analysis for solar panel dust mitigation using an electric curtain[J]. Renewable Energy 41, 134–144 (2012).
9. Qixia Sun, Ningning Yang, and Zhiqian Xiao. The experimental research on standing wave electric curtain dust removal efficiency[J]. Spacecraft Engineering 21(3), 72–79 (2012).
10. G. Q. Liu, and J. S. Marshall. Effect of particle adhesion and interactions on motion by travelling waves on an electric curtain[J]. Journal of Electrostatics 68, 179–189 (2010).
11. C. I. Calle, C. R. Buhler, and M. R. Johansen. Active dust control and mitigation technology for lunar and Martian exploration[J]. Acta Astronautica 69, 1082–1088 (2011).
12. G. Liu, and J. S. Marshall. Particle transport by standing waves on an electric curtain[J]. Journal of Electrostatics 68, 289–298 (2010).
13. Guangming Wu, Tianlan Yin, and Shuai Tong. Study of dust removal by transparent fork electrodes[J]. Integrated Ferroelectrics, [ISSN:1058–4587] (2013)