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Mechanism of Electronic Charging of Coal Mine Dust

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Abstract

The electronic charging of mine dust can cause coal-dust explosion and increase the risk of pneumoconiosis, so it is necessary to take more attention to the study of its electronic charging properties. The mechanism of electronic charging of coal mine dust was investigated in this paper. It was found that the formation and polarity of dust are determined by the energy band structure and of the two contacting sides; then a mathematical model of work function is established in mesoscopic level. The experiments conclude that the work function decreases with the particle size for the dust with same properties, moreover large particles are positively charged and small particles are negatively charged. Finally, the experimental verification of the main particles charged model drive unipolar and bipolar charged modes and confirm the correctness of microstructure and mesoscopic analyses, which furthermore lay the foundation for further research.

Keywords: *mine dust, energy band structure, electronic work function, charged model.*

1. Introduction

Dust is divided into several categories each with its own nature. Scientists began to study the nature of the dust in volcanic plume from the early twentieth century, and reached a conclusion that many new features emerged except maintaining the original chemical and physical properties [1- 6]. In the past two decades, researchers found that dust have charge and other characteristics, and also found the charged dust which is blocked in the respiratory tract, which is responsible for the increasing risk of pneumoconiosis [7-14]. The dust suspended in the gas is insulated by earth, causing the dust with charge and even possible explosion. The surface area of dust is much larger than the solid block of same weight, increasing opportunities for contact with other objects, which also increase the possibility of charged dust. But the official reports about charged mine dust has not been seen in home and abroad. In order to reveal the mechanism of charged dust, this paper explores details within micro-meso-macro levels.

2. Micro-level Analysis

Every dust particle is an agglomerate of several small particles [15-17] .The main composition is carbon, followed by ash, water, etc, and also contains about 5% of the silica and trace metal compounds, etc. A carbon component includes of Carbon atoms, and neuter atom is composed by the positively charged protons and negatively charged electrons. The electron has a series of separate energy levels (1s2. 2s2. 2p2) in a single C-atom [18, 19]. When C contains N identical atoms, the valence electrons originally with a same energy would be in the state of communization, and these communized outer electrons will no longer be in the same energy level, which makes the same energy level split into N new levels closed to the original one. As N is large, the energy difference between the adjacent two levels is small in new energy-level, forming a continuous range of certain energy band with a structure of valence band, forbidden band and conduction band.

When the dust particles in contact with particles or the surface of instrument, the charging process includes two basic steps (contact and separation) as shown in Figure 1. In Figure 1, A1 and A2 indicates that when two different substances happen to contact (dust-dust, dust-surface of instrument), establishing to the binding force of electrons by different substances. The electron energy redistribution at the contact surface produces the formation of a series of interface levels (expressed by short-terms between different substances as shown in

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Figure 1). The interface energy levels receive electrons from one or both contacting sides, depending on the high-low of interface energy levels comparing to material Fermi level or the conduction band minimum. The two contacting sides are separate in B1 and B2. In the separating process and before, interface state is not completely disappear, the interface energy level increases as the role of the separation force, the charge gathered at the interface would move back to dust or the surface of instrument and be recaptured. The number of charges each substance captured is determined by energy levels of dust and instrument surface, so that the charge gathered at contacting surface redistributed in this process and material is charged in two contacting substances. After several contact-separations of these two substances, due to the balance of energy levels, charge inter-transfer would be no longer occurred, and the materials static load reaches to the equilibrium state, and each side brings a contrary polarity to another after separation.

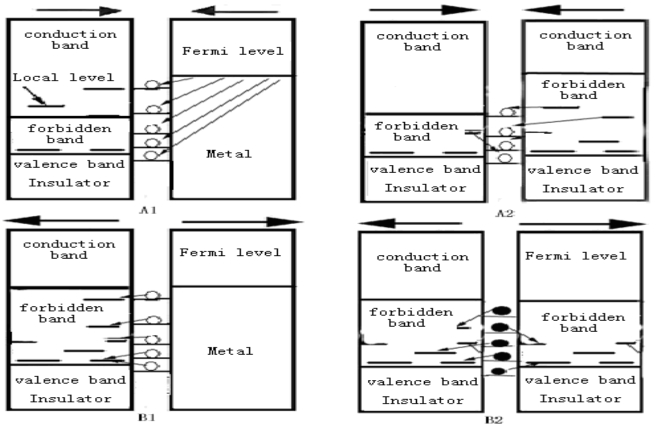


Figure 1. Contact Charging Mechanism Chart

3. Meso-level Analysis

The experimental setup is carried out with setting up an isolated dust particle form a small dust ball with no conductivity. Initially, a mathematical model of effective work function for a dust particle to identify change with particle size and the relative dielectric constant is established, which forms a basis for further research.

3.1. Establishing the Mathematical Model

For simplicity, this paper only discusses the change of energy (i.e. work function), which is required to transfer a change carrier from the dust particle, with the change of parameters. Assuming the electric quantity of a charge carrier is q. As shown in Figure 2, after a charge (power is q) is transferred from a dust particle surface with a diameter R and relative dielectric constant ε_r, the charge (-q) still remaining on the surface. Assuming the distance from the charge (q) to the center of the sphere is r and the distance between two charges is x, then the particle is affected by dual polarization of charge (q) and charge (-q).

In the initial state, the distance x_0 between charge (q) and the particle surface (charge -q) is the initial offset distance. When the particle size is 0 indicates that this model is a charge and it is the lower limit of model; when the particle size is infinite indicates that this model is an infinite plate and it is the upper limit. Work function in the range of $0 \sim +\infty$ is the minimum required energy that transfer a charge, which has the weakest binding strength, from initial offset distance (x_0) to infinity. However the charge with the weakest binding strength has a highest energy level and most likely to be migrated out of the particle surface. From this perspective, work function is the quantitative characterization of contact charging nature of the material with a certain energy band structure and it is same to the essence of micro-analyses.

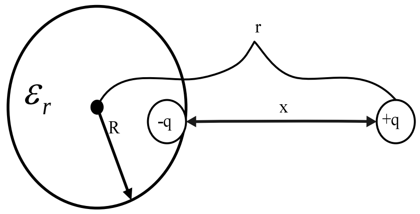


Figure 2. Schematic Diagram of Simplified Model of an Insulating Particle as a Dielectric Sphere

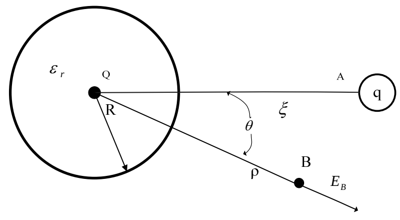


Figure 3. Radial Electric Field at Arbitrary Field Point due to Polarization of Dielectric Sphere by Charge q

In the scenario, the distance between charge (q) and the ball surface is greater than x_0, the electrostatic force the charge consists of three parts:
1) Charge (q) gets coulomb force attraction by charge (-q):

$$F_1 = \frac{q^2}{4\pi\varepsilon_0 x^2} = \frac{q^2}{k(r-R)^2} \quad (1)$$

$k = 4\pi\varepsilon_0$. Then, the force direction that makes the charge carrier away from the ball center is positive, and the other negative is derived.
2) As the dust ball is a kind of polymer, the polarization inside of ball would likely be caused as long as its pluralistic structure meets weakly interference. When charge (q) is transferred out and charge (-q) appears on the ball surface, and due to charge (-q) polarization activity in the ball, the result is giving an impact force to charge (q) as shown in Figure 3.

In Figure 3, under the effect of polarization by charge (q) at point A with a distance of ξ ($\xi \geq R$) from Q, the electric potential φ of any point of isolation ball at B can be expressed as [20-22]:

$$\varphi = -Q(\varepsilon_r - 1)\sum_{n=0}^{\infty} \frac{n}{1+n(\varepsilon_r+1)} \frac{R^{2n+1}}{\xi^{n+1}} \frac{P_n(\cos\theta)}{p^{n+1}} \quad (2)$$

Where $P_n(\cos\theta)$ is Legendre polynomials, Radial electric field strength (E_B) at B is:

$$E_B = -\frac{\partial \varphi}{\partial B} \quad (3)$$

As the charge (Q) projecting the polarization on this ball, the radical force of charge (q) at point B is:

$$F_B = qE_B = -qQ(\varepsilon_r - 1)\sum_{n=0}^{\infty} \frac{n(n+1)}{1+n(\varepsilon_r+1)} \frac{R^{2n+1}}{\xi^{n+1}} \frac{P_n(\cos\theta)}{p^{n+2}} \quad (4)$$

When

$Q = -q, \xi = R, p = r, \theta = 0$,

$$F_2 = +q^2(\varepsilon_r - 1)\sum_{n=0}^{\infty}\frac{n(n+1)}{1+n(\varepsilon_r+1)}\frac{R^n}{r^{n+2}} \quad (5)$$

3) The attraction force F3 is from the polarization inside the sphere be used by q.

$$F_p = -qE_p = qQ(\varepsilon_r - 1)\sum_{n=0}^{\infty}\frac{n(n+1)}{1+n(\varepsilon_r+1)}\frac{R^{2n+1}}{\xi^{n+1}}\frac{P_n(\cos\theta)}{p^{n+2}} \quad (6)$$

Assuming $Q = q, \xi = p = r, \theta = 0$

$$F_3 = -q^2(\varepsilon_r - 1)\sum_{n=0}^{\infty}\frac{n(n+1)}{1+n(\varepsilon_r+1)}\frac{R^{2n+1}}{r^{2n+3}} \quad (7)$$

From above, a total force the charge q suffers is: $F = F_1 + F_2 + F_3$.

The work to transfer charge q from x_0 to infinity is:

$$w = \int_0^{\infty} F.dr = \frac{q^2}{\mathrm{k}\ (r_0 - R)} - q^2(\varepsilon_r - 1)\sum_{n=0}^{\infty}\frac{n}{1+n(\varepsilon_r+1)}\frac{R^n}{r_0^{n+1}} + \frac{1}{2}q^2(\varepsilon_r - 1)\sum_{n=0}^{\infty}\frac{n}{1+n(\varepsilon_r+1)}\frac{R^{2n+1}}{r_0^{2n+2}} \quad (8)$$

Where r_0 is the initial distance from the ball center, and $r_0 = R + x_0$. Thus the mathematical model of the effective work function is established.

3.2. Numerical Simulation

As shown in equation (10), the effective work function w is a very complex variable, and it is difficult to analyze and find the solution for this. So, initially, the numerical simulation is undertaken and the ways to find the solution is discussed.

Based on MATLAB simulation, the diagram can be obtained as shown in Figure 4.

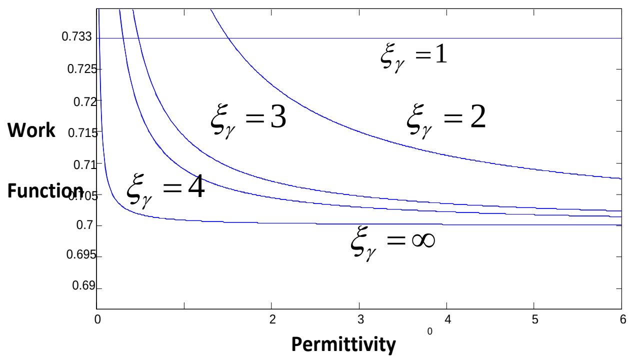


Figure 4. Plot of the Variation on Effective Work Function of Insulator Particle with the Particle Diameter and Relative Dielectric Constant

As shown in Figure 4, as the dielectric constant is identical (i.e. in the same particles nature), the effective work function decreases with the increase of particle diameter as the dielectric constant is diverse (i.e. in different particles nature), the effective work function decreases with the increase of particle diameter size. Comparing to the small article, the bigger one has a small effective work function, so that when two different particles contact the electron are transferred to the smaller one, leading to the smaller particle with negative electricity and the larger with positive.

The relative permittivity of dust particles is generally between 3~6, and when $n(\varepsilon_r + 1) >> 1$, we make use of :

$$\sum_{n=1}^{\infty} \frac{nZ^n}{1+n(\varepsilon_r+1)} \cong \frac{1}{\varepsilon_r+1} * \frac{Z}{1-Z}, \quad Z < 1 \tag{9}$$

Then Equation (8) can be expressed as:

$$w = q^2[(\frac{1}{\mathrm{k}(r_0 - R)} - (\frac{\varepsilon_r - 1}{\varepsilon_r + 1})(\frac{R}{r_0(r_0 - R)}) + \frac{1}{2}(\frac{\varepsilon_r - 1}{\varepsilon_r + 1})(\frac{R^3}{r_0^2(r_0^2 - R^2)})] \tag{10}$$

Where ε_r is higher, the equation is more precise.

3.3. Discussion

1) When R=0, Equation (10) indicates that the required energy transferring charge q out from the point charge:

$$w = \frac{q^2}{\mathrm{k}\, x_0} \tag{11}$$

2) When $R = \infty$, Equation (10) indicates that the work function of infinite flat insulators (including the effects of residual charge):

$$w = q^2(\frac{1}{kx_0} - \frac{3}{4x_0}(\frac{\varepsilon_r - 1}{\varepsilon_r + 1})) \tag{12}$$

3) When $\varepsilon_r = 3$, the work function can be expressed as:

$$w = \frac{q^2}{x_0}\left[\frac{1}{\mathrm{k}} - \frac{1}{2}\frac{R}{x_0 + R} + \frac{1}{4}\frac{R^3}{(2R + x_0)(R + x_0)^2}\right] \tag{13}$$

4) When $\varepsilon_r = \infty$, Equation (10) indicates the required energy transferring charge q out from an infinite polarized isolated dust ball:

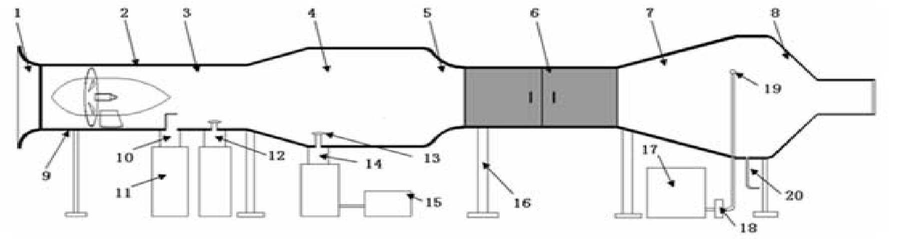
$$w = \frac{q^2}{x_0}\left[\frac{1}{k} - \frac{R}{x_0 + R} + \frac{1}{2}\frac{R^3}{(2R + x_0)(R + x_0)^2}\right] \tag{14}$$

It is observed that, the microscopic variation trend of work function with dielectric constant and the particle size change as microscopic properties changed, and such law in this model mainly manifest in the change of maximum offsets distance x_0 between charge and particle surface. From the energy level perspective, the lower minimum of insulate particles conduction band and the closer of distance between forbidden band local level and conduction band minimum, the more easily the electron transit to the conduction band and the more electron activities are achieved. As shown in the Equation (14), the larger offset x_0, the smaller the particle work function; the larger particle size, the smaller the particle work function and more easily particles charged positively.

4. Macroscopic Experimental Verification

4.1. The Construction of the Experimental Platform

Macroscopically, we use experiment to test the validation on the rationality and validity of the microscopic, mesoscopic analysis, verification of mine dust in the laboratory test system platform, the specific measurement place as shown in Figure 5.



1-Air intake 2-Dynamic section 3-Excessive section 4-Stilling chamber 5-Convergent section 6-Experiments section 7-Extended dust removal section 8-Contraction exhaust section 9-Thermal insulation material 10-Temperature transmitter 11-Instrument support 12-Humidity transmitter 13-Diffusor 14-Aerosol dust generator 15-Air compressor 16-Model support 17-Storage water tank 18-Line pressure pump 19-Blow head 20-Drainage pipeline

Figure 5. The Test System of the Dust Chart

4.2. Experimental Verification

Experiment 1: Clean compressed air is not charged, the collision of charged caused by the air and the wall friction can be neglected.

Let the dry filter clean compressed air into the test system, the flow speed of air is 3-8 m/s and gather the signal of static voltage, the experiment result as shown in Figure 6. Horizontal axis represents time and ordinate represents the static voltage. From Figure 6, we can see that the static voltage is very small, almost zero, which is caused by the trace particle in the air, and can be ignored. It illustrated that the air adopted by experiment was not charged before entering the test system and the collision of charged caused by the air and the wall friction can be neglected.

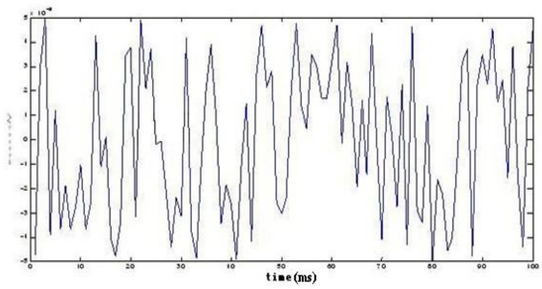


Figure 6. The Static Voltage when Air through the Empty Device

Experiment 2: Validation: the dust particles surface can think not charged after a pretreatment, the charge caused by contact between air and particle collision can be neglected.

Procedure: firstly, send the mean grain size for 5 dust after pretreatment by aerosol generator into the test system of the experimental section; After particles be static, the steady flow transmitter installation send 0.2 of velocity after filtering compressed air to clean measurement system experimental section. The velocity of the clean air of the gas is less than the dust particle starting speed. At the beginning there was no collision among the particles (for static), the test system only had contact and friction between air and wall, and between air and granular at this time. Assume that air and particle collisions can cause significant charged, the air will take away from a polarity charge, the left of air will take away a kind of polarity charge, where the other will remain. However the static voltage measured as shown in Figure 7 shows is almost zero. It is concluded that dust particle surface after pretreatment can be thought of not charged, and demonstrates the charge by contact collision between the air and intergranular also can be neglected.

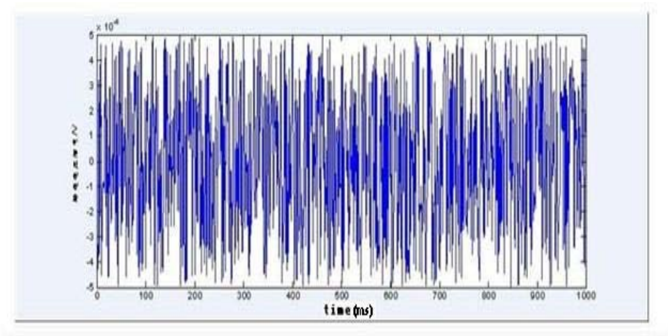


Figure 7. The Static Voltage when Air through the Dust Particles Device

Experiment 3 will verify that the contact charged between particles and wall, experiment 4 will verify that the contact between particles and particles and focus on the charged between large particles and small granule.

Experiment 3: Verification of particle collision with the surface of the instrument.

Material Selection: The raw coal material from mining is chosen, and a 10 g coal dust is obtained with an average particle size of 20 μm through the high-precision grinding machine, and particles are added into the experimental apparatus after full discharge. The ceramic, PVC, plastic drive pipe manufactured by aluminum with a diameter of 500mm and length of 500mm as the material colliding with particles is selected. As there are a few of particles, initially, the collision probability of dust particles with instrument surface is far greater than the collision between particles, so charged dust can be considered caused by the collision with instrument surface. The dielectric constants of four materials are shown in Table 1, and the experimental results after the collision are shown in Table 2.

Table 1. Permittivity of the Test Materials

Material	ε_r
Ceramic	6
PVC	2.8-5.0
Plastic	2-3
Aluminum	None

Analysis of Experimental Results: The Monopole particles are charged by colliding with instrument surfaces in different materials. So that it can be concluded that the contacts between particles have occurred, if any type of dust particles in different sizes were measured with bipolar charge in the movement.

Experiment 4: Contact with Particles

On the basis of experiment 1, this experiment undertakes the verification on the charged quantity and nature of particles in same properties but with different sizes. First of all, the particle about 10 g in sizes of greater than 100 μm and far less than 100 μm is taken. Then particles are put into a vibrator with shocking 600s after sufficiently mixed, and the vibrator is made of PVC material with a diameter 100 mm and length 100 mm. The experimental results are shown in Table 3.

Table 2. Experimental Results of Particles are Charged when Dust Contact with Four Kinds of Materials (nC)

Particles charge Times	particles with Ceramic	Particles with PVC	Particles with plastic	Particles with aluminum
1	-8.05	-4.34	-11.67	-14.10
2	-6.45	-2.16	-11.60	-44.50
3	-4.05	-0.66	-12.30	-34.30
4	-5.65	-3.34	-12.10	-20.48
5	-7.20	-2.95	-7.20	-39.45

Table 3. Charge after the Contact between Large and Small Particles

Particles charge Times	Total charge (nC)	Charge of big particle(nC)	Charge of small particles(nC)
1	-0.08	7.04	-19.56
2	-0.17	3.10	-7.35
3	-1.09	5.04	-7.04
4	-0.21	7.36	-15.44
5	-0.50	2.10	-6.44

The experimental result shows that dust particle's contacts with instrument surface develop a small amount of negative charge to the particles. In the process of separation using the separator, the friction of particles with instrument surface brings decreasing amount of positive charge for the larger particles and an increasing amount of negative charge for the smaller particles, making the overall electric quantity unbalanced. We can observe from the experimental results that the contacts make the small particles negatively charged and large particles positively charged, which correspond to above conclusions. It can also be initially concluded that there are two main charged modes as shown in Figure 8.

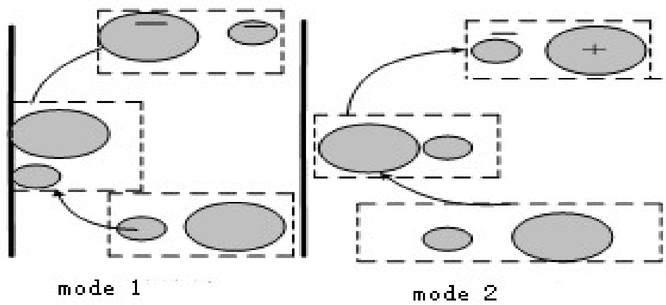


Figure 8. The Schematic of the Dust Charging in Main Mode

Mode 1: Both big and small particles are charged with the same polarity when they contact with all kinds of wall surface. This conclusion is identical with the results of experiment 1, in which four different material surfaces carried negative charge after the contact with particles.

Mode 2: When particles in contact with other particles, particles are bipolar charged and one particle's surface properties would have some impact to the others. Large and small particles would bring the opposite polar charges that mean the small particles with negative charge and large particles with positive charge. These results are identical to that of the experiment 2.

5. Conclusion

The charging process, characteristics and mode of dust charging were investigated from microscopic, mesoscopic and macroscopic levels. And the mechanism of charged dust is clearly illustrated with a multilevel analysis. On the microscopic level, we carryout out analysis work on the dusts' characteristics based on the Band Theory. It is proved that the generating process of electric charge is divided into different steps of contact and separation. The quantity of electric charge and polarity is determined purely by their own band structure. On the mesoscopic level, a mathematical model is established on the basis of the Work Function Theory. The variation tendency of the particles' work function is shown in this paper. When these dust particles have the same size, the work function value decreases as the dielectric constant grows. And if they have the same dielectric constant, the function value decreases as size grows, larger particles are electropositive, while smaller ones are electronegative. On the macroscopic level, our experimental results show the different modes of unipolar and bipolar charged dusts. We hope that, the current study will lay foundation for further research on mine dust charging mechanism.

Acknowledgement

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