Study on Mechanism and Characteristics of Particle Charging In Electrostatic Precipitator

Kexin Zhang\textsuperscript{*}, Shiyu Chen\textsuperscript{a}, Long Tan\textsuperscript{b}, Minhu Xu\textsuperscript{c}, Hongda Zhang\textsuperscript{d}, Dewen Zhang\textsuperscript{e}

State Grid Heilongjiang Electric Power Co. Ltd. Electric Power Research Institute, Harbin, China

\textsuperscript{*}Corresponding author e-mail: 13796039604@163.com, \textsuperscript{a}uniquecharm@live.cn, \textsuperscript{b}418337933@qq.com, \textsuperscript{c}53474033@qq.com, \textsuperscript{d}zhanghongda99@163.com, \textsuperscript{edewen1984@163.com

Abstract. Nowadays, Electrostatic precipitator (ESP) is an important large-scale equipment for reducing dust elimination and reducing pollution in industrial production. As the second working step of ESP, dust charging is very important, and its charge directly affects the subsequent work of the electrostatic precipitator and the dust removal efficiency. In this paper, the charging mechanism of dust particles in the discharge area of ESP is studied. The charge and its influencing factors of dust particles with different particle sizes under different mechanisms are analyzed. The research results have certain effect on how to increase the charge of dust particles. The research in this paper is of great significance to improve the dust removal efficiency of ESP.

1. Introduction
Dust pollution has become one of the main factors restricting the development of society. Due to various advantages, such as high dust removal efficiency, low resistance loss, large amount of treated flue gas, ability to capture highly corrosive dust particles, high temperature resistance and low operating and maintenance costs, Electrostatic precipitator (ESP) has become one of the main pollution prevention devices [1-3]. It has become one of the main research directions that how to improve the dust removal efficiency of ESP.

There are four steps during the working process of ESP, which are gas ionization, dust charging, dust settling and cleaning [4-5]. Dust charging is the second step during the working process. The mechanism of dust charging and the dust charge directly affect the dust movement speed and dust collection efficiency. The mechanism characteristics of dust charging are studied theoretically in this paper. The formula for calculating the dust charge under different mechanisms is derived, which has certain guiding significance for the future research of ESP.

2. Charging mechanism
Dust particles are charged in two ways in electric field: electric field charge and diffusion charge [6]. The ions impinge on the dust particles to charge the dust under the action of the electric field force,
while diffusion charge means that his ions collide with the dust particles to charge the dust particles under the diffusion caused by disorderly thermal motion.

During dust charging, process, the main mechanism of dust charging is different as the different particle radii. When the dust particle radius is greater than 1 μm, the electric field charge is dominant, while for dust particles with a radius less than 0.1 μm, the dominant role is diffusion charge; for particles with a radius of 0.1~1 μm, both play a certain role [7].

3. Charging characteristics

3.1. Analysis Prerequisites
Before the analysis, the following four conditions must be assumed:
1. The dust particles are uniform in size, and all are spherical, and exist in the discharge region in suspension;
2. The electric field generated by the charged dust particles does not affect the electric field near other dust particles;
3. The same dust particles adsorb the same number of negative ions;
4. The applied electric field is locally uniform around the dust particles.

3.2. Electric field charging
The analysis is first started by corona discharge in the cleaning gas. In the cleaning gas, the dust particles are uniform around each partial area according to the analysis Prerequisites. For areas without charge, there is no charge inside and outside the dust particles. As show in Figure 1.

![Fig. 1 The electric field near an uncharged dust particle](image)

According to the Laplace potential equation, it can be inferred.

$$\nabla^2 U = 0$$  

(1)

In the spherical coordinate system, Equation 1 can be written as

$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \frac{\partial U}{\partial r}) + \frac{1}{r^2 \sin \phi} \frac{\partial}{\partial \phi} (\sin \phi \frac{\partial U}{\partial \phi}) = 0$$  

(2)

In Equation 2, there are two types of edge strips to be considered. At the origin, the potential value is a finite value. At infinity, the x component of the electric field strength approaches $E_\infty$. 

When \( r \to \infty \), it can be inferred \( E_r \to E_\infty \cos \theta \). As \( E_r = -\frac{\partial U}{\partial r} \), when \( r \to \infty \), there is \( \frac{\partial U_2}{\partial r} = -E_\infty \cos \theta \).

According to the continuity of the surface electrical edge, at any point on the surface of the dust particles \((a, \theta)\), when \( r = a \), there is \( U_1 = U_2 \).

Part of the surface of the dust particles is selected as the calculation. Permittivity of dust is \( \varepsilon = \varepsilon_r \varepsilon_0 \). Supposing \( q \) is the free charge on the surface of the dust particles, which does not include any induced charge, according to Gaussian energy quantification, it can be concluded

\[
\int \varepsilon_r E dA = \frac{q}{\varepsilon_0}
\]

\( \varepsilon \) is the permittivity of dust. \( \varepsilon_r \) is relative permittivity. \( \varepsilon_0 \) is permittivity of vacuum

Air is almost a complete insulator of which permittivity is \( \varepsilon_r = 1 \), while permittivity of complete conductor \( \varepsilon_r = \infty \).

When \( q = 0 \) and \( r = a \), it can be inferred

\[
\varepsilon_r \frac{\partial U_1}{\partial r} = \frac{\partial U_2}{\partial r}
\]

According to the boundary conditions and the derivation above, the solution of the formula 2 of the dust particles can be obtained as

\[
\begin{align*}
U_1 &= -\frac{2E_\infty}{\varepsilon_r + 2} r \cos \theta \\
U_2 &= -E_\infty r \cos \theta + \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \frac{E_\infty}{r^2} \cos \theta
\end{align*}
\]

From Equation 5, the radial component of the electric field strength of the outer region of the dust particles can be determined as

\[
E_r = -\frac{\partial U_2}{\partial r} = E_\infty \cos \theta + \frac{\varepsilon_r - 1}{\varepsilon_r + 2} E_\infty \frac{2a^3}{r^3} \cos \theta
\]

On the spherical surface of \( r = a \), Equation 6 is equivalent to

\[
E_{ra} = \frac{3\varepsilon_r}{\varepsilon_r + 2} E_\infty \cos \theta
\]

For conductor dust particles, which \( \varepsilon_r \to \infty \), Equation 7 is equivalent to

\[
E_{ra} = 3E_\infty \cos \theta
\]
The above is the charge of the dust particles.

During the actual operation process of ESP, when the dust particles move to the discharge area, the ions collide with the dust particles to be adsorbed to the surface to charge dust particles. Therefore, the assumption that there is no charge on the surface of the dust particles in the above discussion is no longer valid.

Therefore, the influence of the dust particle charge needs to be considered. The trajectory of the dust particles is regarded as a rotational motion when charged, and the electric charge is evenly distributed on the surface of the dust particles.

According to the Gaussian formula, Equation 9 and 10 can be derived.

\[
E_2 = \frac{q_p}{4\pi\varepsilon_0 r^2} 
\]

\[
E_r = E_\infty \cos \theta + \frac{\varepsilon_r - 1}{\varepsilon_r + 2} E_\infty \frac{2a^3}{r^3} \cos \theta + \frac{q_p}{4\pi\varepsilon_0 r^2} 
\]

Making \( q_{ps} = 4\pi D\varepsilon_0 a^2 E_\infty \)

Which D is particle charge coefficient, and

\[
D = \frac{3\varepsilon_r}{\varepsilon_r + 2} 
\]

The following conclusions can be drawn from Equations 9, 10, and 11. The method of increasing the dielectric constant of dust particles in order to increase the charge capacity is feasible within a certain range, but not infinite. The main cause of ion collision is local deformation of the electric field near the dust particles, and the main cause of such electric field deformation is the dielectric polarization of the dust particles in the external electric field and the difference between the dust particles and the dielectric constant of the air.

According to the investigation, taking the dust removal equipment of Taixing Electric Dedusting Equipment Factory in Jiangsu Province as an example, it adopts the needle plate discharge structure, the spacing between the needle plates is 6cm, the halo voltage is -20kV, and the highest voltage of the power supply is -75kV. Therefore, the discharge is set. The range of electric field strength varies from 400kV/m to 1200kV/m. Since the dust particle radius is greater than 1μm, the charging mode is electric field charging. Therefore, the radius of the dust particle is changed from 2μm to 12μm. Figure shows the variation trend of dust particle charge with particle radius and electric field strength under charge.
3.3. Diffused charging

The diffusion charge is independent of the electric field strength of the discharge region. It is caused by the irregular thermal motion of the ions. When diffusing, the ions collide with the dust particles to be adsorbed to the dust particles to charge them. Therefore, the diffusion charge has nothing to do with the effect of the applied electric field. The diffusion charge of the particles depends on the thermal energy of the ions, the size of the dust particles, and the time the dust particles stay in the electric field.

It is assumed that $N$ is the number of ions per unit volume at a certain distance from the dust particles and $N_1$ is the number of ions in the unit volume around the dust particles. According to the theory of motion of gas molecules, the following equation can be used to express the relationship between $N$ and $N_1$.

$$N_1 = N \exp\left(-\frac{e_0 U}{k_0 T}\right)$$

(12)

Where $e_0$ is the charge of ion, $U$ is the voltage at the dust charging and $U = \frac{q_p}{4\pi\varepsilon_0 r}$, $k_0$ is Boltzmann constant, $T$ is absolute temperature.

At the surface of the dust particles of $r = a$, the above formula can be written as

$$N_{1s} = N \exp\left(-\frac{e_0 q_p}{4\pi\varepsilon_0 k_0 T a}\right)$$

(13)

Since the diffusion charge is caused by the random motion of the ions, the charge on the surface of the dust particles arrives in any direction. According to the kinetic energy theory of gas, the number of ions reaching the surface of the particle in the time of $d\tau$ period is $\pi a^2 N_{1s} v_{ef} d\tau$, wherein $v_{ef}$ is the effective rate of the gas molecule.

It is assumed that all ions reaching the surface of the dust particles are successfully adsorbed, increasing the charge of the charged particles, so that the ion current charged by the particles at any time can be obtained:

$$\frac{d(ne)_D}{d\tau} = \pi a^2 N_{1s} v_{ef} \exp\left(-\frac{(ne)e_0}{4\pi\varepsilon_0 a k_0 T}\right)$$

(14)

This equation describes the transient process of ion diffusion charging.
The ions are far apart from the particles so that the ion current is not affected by the charge carried by the particles. Therefore, there is a significant difference between the charging mechanism of ion collision and ion diffusion. The former charging process is limited by the existing charged state and saturation state of the particles. But the latter can only achieve a steady state after an infinite time. Since the condition for this steady state is \( \frac{d(ne)_D}{d\tau} = 0 \), its own equilibrium state must be defined as \( \frac{(ne)e_0}{4\pi\varepsilon_0 ak_o T} \to \infty \), in order to overcome this, the following equation is generally used to describe the steady state

\[
\frac{(ne)e_0}{4\pi\varepsilon_0 ak_o T} = 5
\]  

(15)

The corresponding charged charge of the particle is

\[
(ne)_{SD} = \frac{20\pi\varepsilon_0 k_o T}{e_0} a
\]

(16)

It can be seen that the particle size of the dust particles has a direct influence on the ion diffusion saturated charge.

3.4. The combined effects of two charging mechanisms

In order to illustrate the process of particle composite charging, the charge increment of the particles in the time \( t \) is set to

\[
d(ne) = d(ne)_E + d(ne)_D = \pi a^2 (D(1 + \frac{(ne)}{(ne)_{SE}})^2 + \frac{v_f}{v_l} \exp(-5\frac{(ne)}{(ne)_{SE}})) hid\tau
\]

(17)

Since the maximum value of the electric field charge is used as the reference standard for charging, there is
Wherein $U_m$ Peak voltage between electrodes, $X_m$ is is Electrostatic field shape factor maximum coefficient.

The relative particle charge $\beta$ is defined as the ratio of the charge of the particle to the saturation charge, which is $\beta = \frac{(ne)}{(ne)_{SmE}}$, then

$$(ne)_{SmE} d\beta = \frac{2\pi^2 \varepsilon_0 Da^2}{RF} U_m X_m d\beta$$

$$= \pi Da^2 (1 + \beta \frac{U_m X_m}{UX})^2 h_id \tau + \pi a^2 \frac{\nu_{df}}{bE_\infty} \exp(-\beta \frac{\pi D_e a U_m X_m}{2RFk_0T}) h_id \tau$$

Thereby it can be inferred

$$d\beta = \frac{1}{4\varepsilon_0} ((1 - \beta \frac{U_m X_m}{UX})^2 \frac{UX}{U_m X_m} + \frac{2RF\nu_{df}}{\pi DbU_m X_m} \exp(-\beta \frac{\pi D_e a U_m X_m}{2RFk_0T})) \frac{h_i}{E_\infty} d\tau$$

$hi\over E_\infty$ Is specific conductivity of the dust removal space through when the ion current passes.

$$\frac{h_i}{E_\infty} = \frac{4\varepsilon_0 bU_i}{R^2}$$

Then it can be obtained by the formulas above

$$d\beta = \frac{b}{R^2} (1 - \beta \frac{U_m X_m}{UX})^2 \frac{UX}{U_m X_m} + \frac{2F_{df}}{\pi DRU_m X_m} \exp(-\beta \frac{\pi D_e a U_m X_m}{2RFk_0T})) U_i d\tau$$

The equation obtained above can describe a state that dust particles are gradually charged when they are carried by the airflow through the dust removing space.

It also can be seen from Equation 22 that when the two mechanisms work together, the charge of the ion collision charging is independent of the particle size. The charge obtained by the diffusion charge method is related to the particle size. The smaller the particle size, the more the amount of charge obtained by diffusion charging.

4. Conclusion
In this paper, the mechanism and characteristics of dust charge are studied theoretically studied. The Main conclusions are:

1. There are two main mechanisms for dust charging: electric field charging and diffusion charging. The main charging mechanism is different with the different radii of dust particles.

2. With the mechanism of electric field charging, the charge of the particle increases with the increase of the field strength in the discharge region, and the particle radius, regardless of the temperature.
3. With the mechanism of diffusion charging, the charge of particles increases with the increase of temperature and the particle radius, which is independent of the field strength of the discharge region.

4. Under the combined action of the two mechanisms, the charge of the particles is related to the field strength, temperature, and particle radius.

5. There is a certain saturation value of the particle charge. When the influence of the presence time of the particles in the discharge zone is neglected, the saturation value of the charge is related to the particle radius.

Acknowledgments
This work was financially supported by State Grid research project<Research on Key Technologies of Reliability Improvement of Transmission Channel Operation under Extreme Climate Conditions> (No.5200-201930071A-0-0-00).

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