Charging and absorption characteristics of small particulates under alternative and electrostatic voltages in an electrostatic precipitator*

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The charge quantity of small particulates such as PM2.5 plays a key role in the collection efficiency of an electrostatic precipitator (ESP). Under a single electrostatic voltage, it is difficult to charge and absorb small particulates. A new method of superimposing an alternative voltage on the electrostatic voltage is provided in this paper. Characteristics of small particulates are analyzed under alternative and electrostatic voltages. It is demonstrated that an alternative voltage can significantly improve the collection efficiency in three aspects: preventing anti-corona, increasing the charge quantity of small particulates, and increasing the median particulate size by electric agglomeration. In addition, practical usage with the superposition of alternative voltage is provided, and the results are in agreement with the theoretical analysis.

Keywords: charged characteristics, anti-corona, electric agglomeration, alternative voltage

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1. Introduction

Small particulates such as PM2.5 are not easy to collect in a traditional electrostatic precipitator (ESP) because of their small size and charge quantity,[1] which has a significant influence on the efficiency of dust collection.[2] The fundamental theory of ESP is shown in Fig. 1.[3]

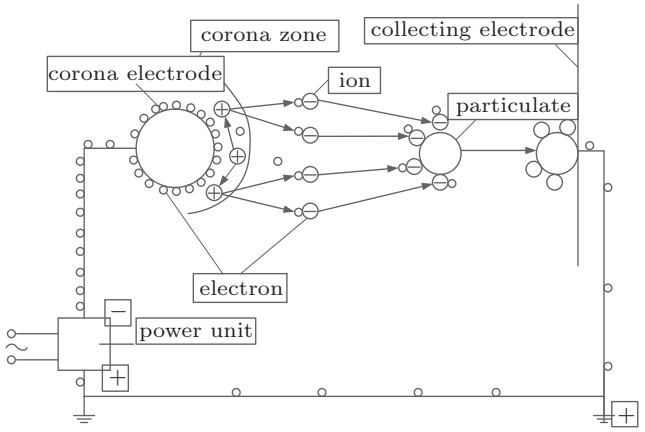


Fig. 1. Principle of ESP.

The process of electrostatic precipitation can be divided into four steps: gas ionization, dust particles charging, dust deposition, and grey clearing. However, in the single static mode, the proportion of small particulates in the dust will greatly increase for two main reasons: the particulates cannot be fully charged, and the phenomenon of an anti-corona can be produced.[4]

In this study, on the basis of charged particulate theory and the formation mechanism of the anti-corona phenomenon,[5] a new method of superimposing an alternative voltage on an electrostatic voltage is proposed. The effect of the alternative voltage in the power supply to prevent anti-corona, the effect on the particulate charge characteristics,[6] and the expansion of the median particulate size are discussed, and their influences on the collection efficiency are investigated.

2. Inhibition of the formation of anti-corona

Anti-corona is a phenomenon of partial discharge generated from the staubosphere on the surface of a dust-collecting electrode.[7] If the dust has a relatively high resistivity, the charge is not easily released.[8] With the thickening of the staubosphere in the collecting electrode, the surface charge of the staubosphere will gradually increase. When the potential difference is larger than the breakdown voltage formed by the dust, the staubosphere will generate a partial breakdown, and resulting in the anti-corona phenomenon. If the dust has a high specific resistance,[9] it is more difficult for the charged dust to be released in the collecting electrode, the generated anti-corona is stronger,[10] the power consumption is higher, and the excessive emission of small particulates is worse. In recent years, anti-corona is becoming an increasingly serious problem because of the wide usage of low-sulfur coal.

In theory, anti-corona can be restrained by an alternative voltage,[11] which can reduce both the potential differ-

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ence and the charge accumulation of the staubosphere. In addition, it can improve the collection efficiency of small particulates by increasing the current density and the electric agglomeration.[12] Therefore, it is necessary to superimpose a suitable alternative voltage on the electrostatic voltage.

3. The effect of alternative voltage on current density and electric agglomeration

3.1. Factors influencing the electric collection efficiency

The collection efficiency is an important performance indicator of an ESP. The dust collection efficiency η is approximately calculated by[13]

$$\eta = 1 - \exp\left(-\frac{qEL}{3\pi\mu dvb}\right), \tag{1}$$

where q is the particulate charge quantity (C), E is the electric field strength (V/m), L is the length of the collecting field (m), μ is the air viscosity (Pa·s), b is the pole pitch (m), v is the flow velocity of the dust (m/s); and d is the median diameter of the particulate (m).

We can observe from Eq. (1) that when the other parameters of an ESP are fixed, the collection efficiency is directly related to the particulate charge quantity.[14]

In the corona discharge caused by a high voltage,[15] ionic groups with a high concentration are generated around the electrode.[16] These ionic groups charge the particulates through a physical process.[17] There are two theories explaining particulate charging, i.e., ion collision and ion diffusion. Because ion diffusion is considered only in a weak electric field, we will mainly consider the effect of ion collision in this paper.[18]

Considering that the collisions of ions between each other can be ignored, we will study only the collisions between ions and particulates. A single ion will be considered to move along the trajectory of the power line caused by the electric field force. When the particulate moves into the electric field, the power line close to the particulate will be deflected and focused on the particulate.[19] After the particulate is charged, it will generate an exclusive electric field to prevent more ions from gathering. With the increase in the particulate charge quantity, the exclusive electric field will also increase. When the exclusive electric field reaches a certain value, the ions cannot reach the surface of the particulate, which means the particulate possesses a saturated charge quantity.

Supposing that the saturation charge is q_s, the ion current density is h_i, which is defined as the ions passing through a unit cross section per unit of time, and the traveled distance of the particulate is p, we can obtain the differential equation of the particulate charge with a tiny space $\mathrm{d}p$[20]

$$\mathrm{d}(q)_E = \frac{\pi c d^2}{4}\left[1 - \frac{q}{q_s}\right]^2 h_i \mathrm{d}p, \tag{2}$$

where c is the particulate charge coefficient, and usually as a constant.

From Eq. (2), we observe that the charge quantity is proportional to the ion current density. With the increase in the ion current density, the charge quantity will increase, and the collection efficiency in the ESP will also significantly increase (see Eq. (1)).

3.2. The effect of alternative voltage on current density

As the ESP can be defined as a capacitor c_p combined with a large resistor, which can be ignored in the circuit, the alternative current is $\mathrm{j}\omega c_p u$, where ω is the angular frequency, and u is the effective value of the alternative voltage. Then, the ion current density is directly related to this current. Therefore, increases in ω and u will increase the ion current density.

Superimposing an alternative voltage on the electrostatic voltage can increase the frequency and amplitude. There are two methods for the superimposition, which is shown in Fig. 2.

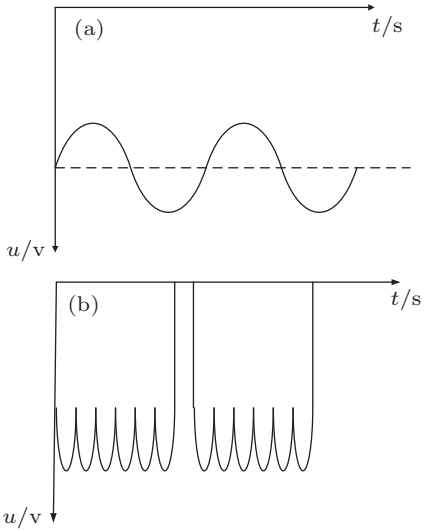


Fig. 2. Methods of superimposing an alternative voltage on the electrostatic voltage. (a) Superposition of two isolated power supplies. (b) Superposition of a single power supply.

The first method (Fig. 2(a)) is complex. It has two isolated power supplies, the alternative voltage is coupled directly with the electrostatic voltage,[21] and the gas discharging will be in a plasma mode.[22] The second method (Fig. 2(b)) is relatively simple. From the on–off control of the electrostatic voltage power supply, the alternative voltage is modulated on the output.[23,24]

The power supply currently being used in the ESP is single-phase rectified DC (direct current) mode, and the output is observed to be a DC voltage superimposed on an alternative voltage. The frequency of the alternative voltage is 100 Hz. If a three-phase-rectified DC power supply is used, the frequency is 300 Hz. In recent years, a DC power supply in a high-frequency switching mode at 20 kHz–50 kHz has begun to be used. It can be predicted that the best working mode for

the ESP is to use a high-frequency switching mode DC power supply with an on–off control (Fig. 2(b)), which can significantly increase the ion current density and will revolutionize this area.

3.3. The effect of alternative voltage on electric agglomeration

Electric agglomeration is a basic method of expanding the diameter of a particulate.[25] In electric agglomeration, the charged particulates vibrate under the force of an electric field, which causes the particulates to collide with each other and agglomerate. Currently, the methods of electric coagulation include the following three types: agglomeration of the charged particulates with different polarities in a DC electric field,[26] agglomeration with the same polarity in an alternative electric field,[27] and agglomeration with different polarities in the alternative electric field.[28] In an alternative electric field, charged particulates with different polarities vibrate, which can significantly improve the agglomeration rate.[29] Our analysis will now focus on this method.

Assume the diameters of two particulates are d_1 and d_2, their velocities are v_1 and v_2, their masses are m_1 and m_2, their charges are q_1 and q_2 respectively, and the agglomeration factor K is given by collision theory

$$K = \frac{\pi}{4}(d_1+d_2)^2|v_1-v_2|. \tag{3}$$

If the particulate is small ($d < 5$ μm) and when the inertia is ignored, the velocity of the particulate is

$$v = qE\sin\omega t/3\pi\mu d. \tag{4}$$

The charge quantity of the particulate is

$$q = \frac{3}{2+\varepsilon}\pi\varepsilon_0\varepsilon E d^2, \tag{5}$$

where ε is the relative permittivity of dust, ε_0 is the permittivity of air, and $\varepsilon_0 = 8.85\times10^{-12}$ C/(V·m).

Using Williams' method, we obtain the agglomeration factor as

$$K = \frac{1}{2}(d_1+d_2)^2\left(\frac{\tau_1 q_1 E}{m_1}\cos^2\varphi_1 + \frac{\tau_2 q_2 E}{m_2}\cos^2\varphi_2\right), \tag{6}$$

where

$$\cos\varphi_1 = \frac{1}{\sqrt{1+\tau_1^2\omega^2}}, \quad \cos\varphi_2 = \frac{1}{\sqrt{1+\tau_2^2\omega^2}},$$

τ is the relaxation time with $\tau{=}\rho_{\rm d}d^2/18\mu$, and $\rho_{\rm d}$ is the dust density (kg/m^3). As τ_1 and τ_2 are very small, $\tau_1^2\omega^2 \ll 1$ and $\tau_2^2\omega^2 \ll 1$, then

$$K = \frac{1}{2}(d_1+d_2)^2\left(\frac{\tau_1 q_1 E}{m_1} + \frac{\tau_2 q_2 E}{m_2}\right). \tag{7}$$

Therefore, we obtain the result that the frequency ω has no influence on the agglomeration factor.

Using another method, considering that the particulate has a very small mass, and the inertia has an insignificant effect, we have the agglomeration factor K in the alternative electric field:

$$\begin{aligned} K &= \frac{\pi}{4}(d_1+d_2)^2\frac{\omega}{\pi}\int_0^{\pi/\omega}|v_1-v_2|\,{\rm d}t \\ &= \frac{(d_1+d_2)^2 E}{6\pi\mu}\left(\frac{q_1}{d_1}+\frac{q_2}{d_2}\right). \end{aligned} \tag{8}$$

Equation (8) also shows that when the inertia is ignored, the agglomeration factor of a particulate is independent of the frequency. However, the factor K is in proportion to the amplitude of E, which is related to the amplitude of the alternative voltage. For a particulate with a diameter of 0.5 μm, when $E = 4$ KV/cm, $c = 6$, and $\mu = 1.82\times10^{-5}$ Pa·s, we obtain the agglomeration factor $K \approx 10^{-14}$ m^3/s, which is in agreement with the experimental results.[30]

The particulate median diameter $d(t)$ is

$$d(t) = \left[1+\frac{1}{2}KN_0t\right]^{1/3}d_0, \tag{9}$$

where N_0 is the initial count concentration of the particulate before the electric agglomeration, and d_0 is the initial median diameter.[31]

Assuming that $N_0 = 1.2\times10^{14}$ m^3/s, $c = 6$, and $\mu = 1.82\times10^{-5}$ Pa·s, the median diameters of particulates at $E_0 =$ 100, 200, and 300 V/cm, E_0 is the peak field strength (V/cm), the relationship of the median diameter $d(t)$ with E_0 is shown in Fig. 3.

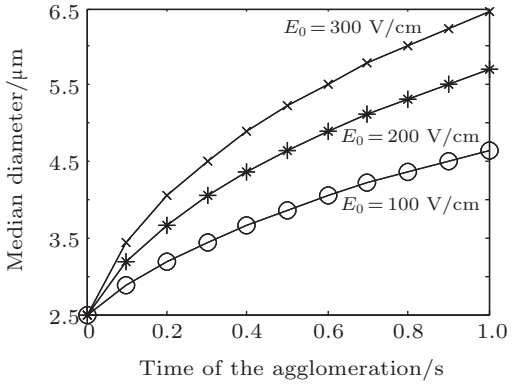


Fig. 3. Relationship of $d(t)$ with E_0.

Figure 3 shows that in one second, when $E_0 = 100$, 200, and 300 V/cm, the median diameter of the particulates increases from 2.5 μm to 4.6, 5.7, and 6.5 μm respectively.

Therefore, we can conclude that the alternative voltage can effectively increase the particulate diameter through the agglomeration factor, which is related to the alternative voltage amplitude.

3.4. Effects of ion current density and particulate size on the collection efficiency

When $E_0 = 4$ kV/cm, the electrode distance $b = 40$ mm, the length of the collecting field $L = 1$ m, and the saturation charges of the particulate with diameters of 2.5 μm and 5 μm are 1.563×10^{-16} C and 6.252×10^{-16} C respectively. According to Eq. (1), the collection efficiencies of the particulates with diameters of 2.5 μm and 5 μm are shown in Fig. 4.

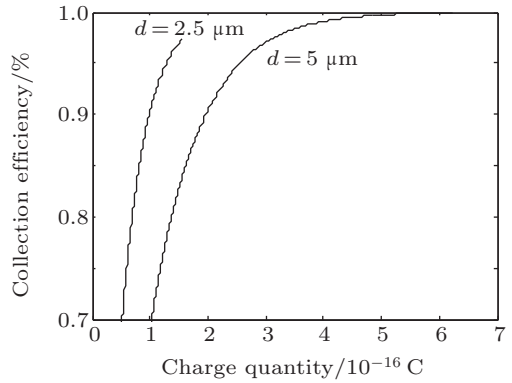


Fig. 4. Collection efficiency.

Figure 4 shows that when the median particulate diameter is 2.5 μm, the collection efficiency is as high as 97.3% because it has a saturation charge. When the diameter expands to 5 μm, the particulates have a higher charge quantity, and the collection efficiency increases to 99%. This figure also shows that when the particulate diameter is constant, the collection efficiency increases with the charge quantity. The charge quantity increases with the ion current density, and an improved efficiency is obtained.

Our conclusion is also demonstrated by the practical data of one steel mill, as shown in Table 1. Before the transformation, the power supply in the ESP is in single-phase rectified DC mode. After the transformation, a three-phase rectified DC power supply is used, and from the method using an on–off control, a large amplitude alternative voltage is superimposed on the ESP, as in the waveform in Fig. 2(b).

Table 1. Comparison of the particulate emissions before and after the transformation.

	Before transformation	After transformation
Gas velocity/m·s^{-1}	13.8	15.1
	15.4	14.3
	18.4	19.9
	15.8	18.4
	16.4	13.2
Particulate density/mg·m^{-3}	13.7	3.1
	10.5	1.2
	53.5	18.4
	22.6	11.2
	16.5	3.7

Table 1 shows that because of the change in the power supply, the efficiency of the ESP is obviously improved by superimposing the alternative voltage. We can imagine that if a high-frequency switching mode power supply at 20 kHz–50 kHz is used, the efficiency can be significantly improved.

4. Conclusions

Two shortcomings exist in the traditional ESP, large power consumption and low absorption efficiency, especially for small particulates. From the charged particulate theory, we find two reasons for the shortcomings: a particulate cannot be fully charged, and the phenomenon of anti-corona exists. By analyzing the charging and absorption characteristics of a small particulate under alternative and electrostatic voltages, we find that the alternative voltage significantly improves the collection efficiency. It can prevent anti-corona, increase the charge quantity of a small particulate through the ion current density, and increase the median particulate size by electric agglomeration. Finally, a practical method of superimposing an alternative voltage on the electrostatic voltage is provided. We also prove that this method can solve the main problems of the traditional ESP.

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