Mechanism and Effect Analysis of Typical Condensation on Dust Particle Aggregation

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Abstract. The removal of industrial dust is mainly realized by various dust removal equipment. The electrostatic dust remover can remove more than 99.5% of the dust particles of various diameters, but the dust removal effect of particulate particles is not significant. Among them, for the finer particles in the dust, the dust removal effect is poor. After measurement, the efficiency of electrostatic dust removal is 80%-85% for fine particles with a particle diameter of 10-1μm [1]. With our higher demand for particulate emissions, improving the removal of industrial fine particulates is imminent. In the process of dust generation, dust particles collide or come into contact through various paths, thereby combining to generate larger particles, and this process becomes the condensation of dust. The dust agglomeration technology is generally used as a pre-treatment of the flue gas in the field of flue gas dust removal. By enriching the fine particles, the fine particles become larger, and then the dust is removed through the dust removal device.

1. Coagulation technology development process

1.1. Electric field coagulation and technology
Until 1960, Fuchs derived a reasonable formula to calculate the collision frequency and applied it to the motion of charged particles [2]. From 1988 to 1989, Eliasson first theoretically calculated the effect of dust condensation with different charge, and then conducted experiments. It was determined that the dust condensation efficiency was consistent with theoretical calculations [3]. William applied the perfect electric field theory to the direction of charge condensation and further improved the formula of the electric field condensation of dust [4]. In 1990, Watanabe studied the law of movement of dust with the same charge in a changing magnetic field, thereby inventing a three-zone distributed electrostatic precipitator [5]. Kauppinen et al. focused on the study of finer dust particles, and analyzed the change of concentration of charged dust particles in a periodically changing electric field to find out the calculation method of concentration change with time in the agglomeration process [6]. Kim will simulate the enrichment efficiency in the model by analyzing samples of various grain sizes. And take experiments to adjust the dust collector model placed in the high-speed air flow, through adjusting the wind speed conditions, so as to achieve higher efficiency [7]. Dumitran measured the movement of particles under laboratory conditions and correlated their movement patterns with the collection of particles [8]. Soldati simulates the effect of particle movement on dust collection in the presence of charged particles. The result is that the charged body has little effect on the dust collection effect [9].
1.2. Sound coagulation and technology
The sonic coagulation of dust and its development in foreign countries were studied earlier. Foreign researchers have conducted long-term research on sound coagulation and technology. When Patterson studied the changes in aerosol and sonic fields, he discovered that MgO would have a phenomenon of enrichment when placed in sonic nodes [10]. In the long-term study of cyclone dust collectors, Fahnoe sonicated NaCl colloids with a particle size of 1 μm, which greatly improved the effect of dust removal [11]. Mednikov realized that sound and coagulation technology is a forward-looking dust agglutination technology for dust removal, and scientifically summarized previous experiments and theories [12]. Aerosol as the breakthrough point in the sound-coagulation process, Scott treated ZnO in sawtooth sound waves and further improved the dust coagulation effect [13]. Gallego-Juárez studied the aggregation of 0.5-0.7 μm carbon black particles in the acoustic wave, and found that the carbon black particles had coalescence and the diameter of the carbon black particles increased to about 10 μm. [14]

1.3. Magnetism and Technology
Tsouris studied the coagulation of magnetic particles in a magnetic field. It was found that the magnetization of particles and the diameter of magnetic particles had a great influence on the coagulation of magnetic particles. [15] Ritter Ja, through theoretical analysis of previous systems, proposes that magnetic materials will generate a magnetic field around the body after being magnetized, thereby interfering or superimposing with the strength of the original magnetic field. Particles that appear as magnetic materials are attracted by the magnetic force around the material that provides the original magnetic field [16]. Ukai T established the model and moved the magnetic particles placed in the magnetic field in dynamic coordinates to analyse the enrichment process of the magnetic material particles in the magnetic field [17].

2. Dust condensation mechanism
2.1. Spontaneous coagulation of dust particles
Dust particles will inevitably collide with the gas flow, so that the colloidal particles will agglomerate and make the particles larger. In fact, in addition to the influence of external forces, the temperature of the fluid will cause the dust to collide due to Brownian motion. We call Brown the cause of this collision. The larger the dust particles, the smaller the factors affected by Brownian motion. So the general particle diameter is less than 1 μm. Brownian motion is the main factor that produces agglomeration. On the contrary, if the particle radius is larger, the diffusion effect is more significant than that of Brownian motion during the coagulation process.

2.2. The condensation of dust particles under the effect of electric field force
Electrostatic precipitators in power plants use the charge on particles. For the use of electric fields to enrich dust particles, the Coulomb force between dust particles can be expressed by the following formula [18]:

\[ W(r) = \frac{q_1 q_2}{4\pi \varepsilon r} \]

In the formula, \( q_1 \) and \( q_2 \) are the quantities of the particles that generate the Coulomb force of the electric field; \( \varepsilon \) is the permittivity between the particles; \( r \) is the distance between the two particles that produce the Coulomb force.

In general, we assume that particles are spherical and appear as monodisperse aerosols. In this state, if the particles are charged with the same kind of charge, the presence of the electric field makes the dust less effective because of repulsion. For particles with the same number of charges, in principle, due to the existence of repulsive forces between particles, it is not conducive to the aggregation of particles. However, in practice, dust samples are highly dispersed in aerosols and their shape and distribution are variable.
2.3. The condensation of dust particles under the action of sound waves

The process of sound coagulation is relatively complex. While sound waves pre-treat the particles, the propagation of sound waves drives the vibration of the particles and causes the particles to become entangled in the sound current. The number of particles measured in the experiment showed a gradual downward trend compared with the inlet data, showing that the density of particles in the fixed space gradually decreased, and the distribution curve of the dust particles in the airflow also changed, the largest number of particle size increased direction offset. The sonic condensation of dust particles is shown schematically in Figure 1.

Figure 1. Sound coagulation and process schematic.

2.4. Coagulation mechanism under magnetic field force

When a magnetic field is applied to dust particles, the particles are subjected to gravity and the force of the fluid, as well as the magnetic force of the particles and the interaction between dust particles. Under different assumptions, the forces that the particles receive in the flow field are also different, and the movement patterns will change accordingly. The direction of the magnetic field shown in the figure is from outside to inside.

3. Effect of Different Condensation Methods on Condensation of Dust Particles

3.1. Electrocoagulation and dust removal

The most important step of electrostatic precipitators is to charge dust particles. In electrostatic precipitators, dust particles are charged in two main ways. One is that the ions move due to the force of the electric field. When the particles move, they combine with the particles that are in contact with them. When the particles are charged, they are called collision charges. The other is due to the diffusion of ions moving in the flow field, which causes the particles to be charged in diffusion, called diffusion charge.

The particle enters the additional electric field region from the entrance for t seconds and the charge on the particle is:

\[ q(t) = \pi \left( \frac{3\varepsilon}{\varepsilon_1 + 2} \right) \varepsilon_0 E_0 d_p \left( \frac{1}{1 + t_0 / t} \right) \]  

Where \( q \) is the amount of electricity charged by the dust particles, \( C; \varepsilon_0 \) is the dielectric constant, \( \varepsilon \) is the relative dielectric constant, \( d_p \) is the particle diameter, \( m; E_0 \) is the field strength of the particle as it enters the magnetic field, \( V/m; t_0 \) is the charging time constant, \( \text{and } t_0 = 4\varepsilon_0 / N_0 eb_s; N_0 \) is the ion concentration, \( N/m^3; e \) is the unit charge, \( C; b \) is the mobility of ions \( m^2/(V \cdot s) \).

For ions moving in an electric field, the particles in the fluid collide with ions to carry a charge due to thermal motion. Although the charge on the particles will increase with time, and the repulsion will reduce the probability that the ions will approach the ions, according to the law of molecular motion, the kinetic energy of the ions moving in the flow field will not reach the limit. The amount of charge carried by particles under diffusion is calculated as:
\[ n = \frac{2\pi e_0 kT d_p}{e^2} \ln(1 + \frac{e^2 ud_p N_0 t}{8e_0 k t}) \] (4)

In the formula: \( k \)—Boltzmann constant, \( 1.3810 \times 10^{-23} \text{J/K} \); \( T \)—Absolute temperature of gas, K; \( N_0 \)—Ion density; \( e \)—Electronic power, \( e = 1.610 \times 10^{-19} \text{C} \); \( u \) is the average thermal motion velocity of gas ions, m/s. It can be seen from the equation that the charge amount of the particles is greatly affected by the change of the particle concentration, and the internal field strength of the applied electric field is the main factor affecting the ion concentration.

In Figure 2, in the region of different particle sizes, the particles dominate the charging mode under the action of an additional electric field.

3.2. Acoustic coagulation

With the increase of sound intensity and the increase of the residence time of particles in the acoustic field, the coagulation effect of dust particles is significantly improved. Mainly because the greater the sound intensity, the increase of the amplitude makes the vibration of the dust particles increase, and the collision effect of the dust particles in the flow field is enhanced. There is no systematic theory on the influence of the frequency on the coagulation effect in the sound field. Only relevant experiments have been carried out to prove that the acoustic wave condensation does have the best value at different frequencies. Table 1 summarizes the superior or optimal frequencies favored by sonication in existing particle sonication and technical studies.

Table 1. The best frequency of coagulation with different particle sizes and the effect of coagulation in experiments

| Years | Particle properties | Optimal frequency/kHz |
|-------|---------------------|-----------------------|
| 1995  | The largest particle size distribution, \( PM_{2.5} \) with a particle size of 0.8\( \mu \)m | 21 |
| 1999  | The largest particle size distribution, \( PM_{10} \) with a particle size of 1\( \mu \)m | 20 |
| 2000  | The largest particle size distribution, Particle size interval 0.02 ~ 0.7\( \mu \)m particles | 20 |
| 2009  | Particle size distribution accounted for three peaks, Particle size is 0.10, 0.76, 1.95\( \mu \)m | 1.4 |
The median particle size of the particle mass is 14.36 μm.

3.3. Magnetic coagulation

At present, the study of magnetic coagulation mainly relies on Lorentz force after the dust is charged to cause the particles to coagulate, so the magnetic coagulation must be recharged. The actual working conditions of the electrostatic precipitator are shown as the simulation of the change of the median diameter of the particles after coagulation and the median diameter of the pre-particles.

Figure 3. The median diameter of the particles after coagulation changes with the median diameter of the pre-particles.

According to Fig.4, the dust removal efficiency increases as the particle condenses and the diameter of the pre-charged particles increases. Compared with the case of no magnetic field condensation, the dust removal effect of charged particles is higher than that of non-condensation. When the charged particle diameter is less than 1.8 μm, the percentage of dust removal efficiency increases as the diameter of the dotted particle increases. When the charged particle diameter is larger than 1.8 μm, the percentage of dust removal efficiency increases as the particle size increases.

4. Conclusion

(1) Acoustic coagulation has not yet formed a comparative system theory as an indicator or trend prediction for determining the effect of dust particle coagulation. However, it has a series of advantages such as energy saving, no pollution, and simple operation, which can be applied to a wide range of fields.
(2) For magnetic coagulation and when the particle size is larger than 1μm, the percentage increase of the coagulation coefficient increases as the particle size increases, and finally tends to be gentle. When the particle size is less than 1μm, the percentage increase of the coagulation coefficient increases as the particle size decreases, and the rate of increase is fast.

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