Numerical Simulated and Mechanism Research on Fine Particle of Pigsty Removal in the Coupling Effect of Acoustic Wave and Electric Field

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Abstract. For improving the collection efficiency of electrostatic precipitator (EP) in the pigsty, MATLAB & Finite element method (FEM) is applied to calculate RNG k-ε equations, corona equation and acoustic radiation equations to analyze sound field, electric field and particle trajectory in the wire-plate EP. The results show that fine particle agglomeration can be induced, so as to promote the enlargement of fine particles and improve the capture efficiency of fine particles at acoustic node area. Moreover, the particle distribution can be controlled according to the above V-η curve in the pigsty. In addition, η initially increases, and then decreases in the range of f from 1000 Hz to 2000 Hz. Therefore, the linear variation law of V– η & SPL – η & f – η provide scientific control method for the construction of green and efficient removal technology of particulate pollutants in the piggery.

Keywords: air quality of the pigsty; fine particles; electrostatic precipitators; airflow velocity; mode.

1. Introduction
With the rapid development of green and sustainable energy collection technology, a large number of suspended particulate pollutants will be produced in pigsty, the main component of which is fine particulate particle (PM2.5, aerodynamic diameter ≤ 2.5 μm) [1, 2]. These fine particles are the carriers of bacteria, viruses and other microorganisms. For example, African classical swine fever virus can spread through short-range aerosol [3, 4]. In addition, more toxic and two pollution will be produced when these bacteria, viruses and NH3 are adsorbed on the surface of particles of pigsty [5, 6]. These reaction process can increases the incidence rate and mortality rate of respiratory diseases, and will worsen the air quality of the pig farm [7-9].

The principle of EP technology is that electrostatic particles are ionized, and the corona effect is generated after the electrode is connected with high-voltage electricity [10]. For example, Wu et al. introduced EP for removing particle in pigsty, and the results show that the device can remove 70% of...
dust particle in pigsty. However, the above experimental results also show that the collection efficiency of fine particle PM2.5 by EP is lower than that of large particles [11, 12]. Note that, acoustic agglomeration can cause particles to oscillate and collide. Multiple fields are used together to produce multi field synergistic promotion effect and realize efficient removal of fine particles.

In this paper, to explore the dust removal rule of PM2.5, a new idea of line-plate acoustic combined electrostatic space charge system (AESCS) was proposed for improving the collection efficiency. MATLAB & FEM is used to conduct multi-field coupling of flow field, electric field and sound field to simulate the dust removal process. And the influence of sound pressure level, sound wave frequency and other factors on the dust removal efficiency of linear plate electrostatic precipitator after adding sound waves was explored. The research results can provide some theoretical guidance for the optimization and design of line-plate EP, and put forward a feasible scheme for the construction of green and efficient removal technology of particulate pollutants in the pigsty.

2. Methods
A schematic of fine particle pollutant removal in pigsty under the action of acoustic wave combined electrostatic precipitator in this study is depicted in Figure 1. The device is composed of acoustic generator (AG), corona wire (CW), collecting plate (CP), aerosol channel, electrostatic control component, etc. The device is called acoustic combined electrostatic space charge system (AESCS). In fact, the dusty air in the atmosphere enters the pigsty through the air inlet system in the current intensive pigsty. Then, the dusty air mixed with the particulate pollutants generated in the pigsty enters the inlet of AESCS. Based on the acoustic agglomeration effect and corona effect, particles or dust is captured by the CP under the action of acoustic radiation force, electric field force and fluid drag force to realize the adsorption of particle pollutants. Utilizing AESCS, the air quality in the pigsty can be improved, and a green and low emission pig farm air circulation will be formed.

3. Numerical model
The governing equation of acoustic radiation effect of AESCS is given, as follows:

\[ \nabla \cdot \left( \frac{1}{\rho_c} \left( \nabla P_t - q \right) \right) - \frac{\omega^2 P_t}{\rho_c c^2} = Q \]

where \( \rho_c \) is fluid density, \( P_t \) is sound pressure, \( q \) is dipole source, \( \omega \) is angular frequency, \( c \) is sound velocity, \( Q \) is monopole source.

The governing equation of corona effect of AESCS is given, as follows:

\[ \begin{cases} \nabla \cdot J = 0 \\ J = \varepsilon_0 \nabla V + \rho u \\ \varepsilon_0 \nabla^2 V = -\rho_q \end{cases} \]
Where \( J \) (SI unit: A/m\(^2\)) is the current density, \( z_q \) is the charge number, \( \gamma \) (SI unit: m\(^2\)/V\(\cdot\)s) is the mobility, \( \rho q \) (SI unit: C/m\(^3\)) is the space charge number density, \( E \) is the electric field, \( u \) is the fluid velocity (SI unit: m/s), \( V \) is electric potential, and \( \varepsilon_0 \) is the vacuum permittivity.

In this paper, the \( k-\varepsilon \) turbulence equation is used, which is based on the observation of the variation of velocity \( (u) \) of convective field with time. By introducing two additional transfer equations and two variables (turbulent kinetic energy \( k \) and turbulent energy dissipation rate \( \varepsilon \)), \( \mu_T \) can be calculated. \( k-\varepsilon \) model is as follows:

\[
\mu_T = \rho C_{\mu} \frac{k^2}{\varepsilon} \tag{3}
\]

\[
\rho \frac{\partial k}{\partial t} + \rho u \cdot \nabla k = \nabla \left( \left( \mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right) + \rho k - \rho \varepsilon \tag{4}
\]

\[
P_k = \mu_T \left( \nabla u : (\nabla u + (\nabla u)^T) - \frac{2}{3} (\nabla \cdot u)^2 \right) - \frac{2}{3} \rho k \nabla \cdot \nabla u - \frac{\varepsilon}{e} \tag{5}
\]

Where: \( k \) is turbulent kinetic energy, \( \varepsilon \) is the turbulent energy dissipation rate, \( \sigma_k \) and \( \sigma_\varepsilon \) are Planck constant, respectively. \( C_{\mu}, C_{\varepsilon 1} \) and \( C_{\varepsilon 2} \) are empirical constants. The velocity, pressure and vorticity distribution can be obtained utilizing the Equations (3) ~ (5).

The relationship between effective sound \( (P_e) \) pressure and sound pressure level \( (SPL) \) can be calculated by the following formula:

\[
SPL = 20 \log \frac{P_e}{P_{ref}} \tag{6}
\]

Where \( P_{ref} \) is reference sound pressure \( (2 \times 10^{-5} \text{ Pa}) \)

Capture efficiency (\( \eta \)) is an important index to measure the performance of electrostatic precipitator, which is defined as:

\[
\eta = \frac{N_1 - N_2}{N_1} \times 100\% \tag{7}
\]

Where, \( \eta \) is the capture efficiency; \( N_1 \) and \( N_2 \) are the number of particles at the inlet and outlet of AESCS, respectively.

4. Results

Figure 3 shows the sound field distribution generated by the sound wave generator in the front section of the electrostatic precipitator. It can be seen from the figure 3 that the sound field presents peaks and troughs in the X-direction. In this node area, fine particle agglomeration can be induced, so as to promote the enlargement of fine particles and improve the capture efficiency of fine particles.

**Figure 2.** Electrostatic precipitator sound field distribution

Figure 3 shows the relationship between particle collection efficiency (\( \eta \)) and particle diameter (\( R \)) at \( SPL = 100 \text{ dB}, u = 1 \text{ m/s and } V = 20 \text{ kV} \). It is noteworthy that \( \eta \) decreases with the increase of \( R \) when \( R \) is from 0.01 \( \mu \text{m} \) to 0.1 \( \mu \text{m} \); then, \( \eta \) hardly changes with \( R \) when \( R \) is from 0.1 \( \mu \text{m} \) to 0.5 \( \mu \text{m} \), and the value of \( \eta \) is about 32%; then, \( \eta \) increases with \( R \) until \( \eta = 100\% \) when \( R \) is from 0.5 \( \mu \text{m} \) to 5.0 \( \mu \text{m} \);
Finally, \( \eta = 100\% \), it means that the particles are completely captured by the collecting plate when \( R \) is from 5.0 \( \mu m \) to 10.0 \( \mu m \). Therefore, the capture law of fine particles with different diameters by acoustic assisted electrostatic precipitator can be presented.

![Figure 3](image3.png)

**Figure 3.** Relationship between particle diameter and collection efficiency when \( R \) is from 0.01 \( \mu m \) to 10 \( \mu m \).

Figure 4 shows the relationship between particle collection efficiency and corona line voltage when \( SPL = 130 \) dB, \( u = 1 \) m/s. it can be seen that \( V-\eta \) is linear growth curve when the corona line is applied by high voltage for \( R = 0.2 \) \( \mu m \) and 2.0 \( \mu m \). It is because than when \( V \) increases, the electric field intensity in the EP also increases, then the electric field force on the particles with PM2.5 increases, and the migration effect of fine particles to the collecting plate is strengthened, so that \( \eta \) enlarge. It is noteworthy that the rise of \( V \) in the lower voltage range has a positive effect on increase of \( \eta \). However, for \( R = 2 \) \( \mu m \), the improvement effect of \( \eta \) is not obvious when the voltage reaches 45 kV. Therefore, the particle distribution can be controlled effectively according to the above \( V-\eta \) curve in the pigsty and removal effect of PM2.5 can be improved.

![Figure 4](image4.png)

**Figure 4.** Relationship between \( \eta \) and \( V \)

The relationship between the collection efficiency and the sound pressure level under different particle sizes is presented in Figure 5. Here, \( V, u \) and \( f \) are 30 kV, 1 m/s and 1000 Hz, respectively. As illustrated in this figures, \( \eta \) increases with \( SPL \) in the above three particle sizes. For example, the collection efficiency is calculated to be 91\% when \( SPL \) is 150 dB for \( R = 1.0 \) \( \mu m \). It is seen that the influence of sound pressure level on dust removal efficiency is linear in the range of \( SPL \) from 130 dB to 150 dB. However, the sound pressure level can not increase indefinitely in actual production. This is because the higher the sound pressure level, the greater the energy consumption; Simultaneously, the existing dust particles on the dust collection plate will be shaken down by the excessive \( SPL \) and return to the mainstream area, causing secondary dust raising and reducing \( \eta \). Therefore, \( SPL \) of 130 dB - 150 dB is the better parameter control range.
The relationship between the collection efficiency and the acoustic frequency under different particle sizes is presented in Figure 6. Here, $V$, $u$ and $SPL$ are $30\, \text{kV}$, $1\, \text{m/s}$ and $150\, \text{dB}$, respectively. It can be seen that the $\eta$ initially increases, and then decreases in the range of $f$ from $1000\, \text{Hz}$ to $2000\, \text{Hz}$. Note that the collection efficiency reaches its maximum value near $1600\, \text{Hz}$. For example, the collection efficiency is calculated to be $98\%$ when $f$ is $1600\, \text{Hz}$ for $R = 1.0\, \mu\text{m}$. In fact, the entrainment coefficient of acoustic wave to particles is large when the acoustic frequency is low range. Simultaneously, the velocity difference of different particles is small, so, the probability of collision agglomeration is small and the agglomeration effect is not obvious. On the other hand, the entrainment coefficient of sound wave to particles is small when the sound frequency is high range. Simultaneously, the particles basically do not oscillate under the action of sound wave, so, the probability of particle collision is very low, and the agglomeration effect is still very obvious. Therefore, above $f-\eta$ curve can be a control function for an optimal frequency range of sound wave.

5. Conclusion

In order to improve the collection efficiency of electrostatic precipitator in the piggery, open source software (MATLAB) & Finite element method (FEM) is applied to calculate RNG $k$-$\varepsilon$ equations, corona equation and acoustic radiation equations to analyze sound field, electric field and particle trajectory in the wire-plate EP. Through deep insight into the particle transport behaviors in a wire-plate EP, the results show that fine particle agglomeration can be induced, so as to promote the enlargement of fine particles and improve the capture efficiency of fine particles at acoustic node area. Moreover, the particle distribution can be controlled according to the above $V-\eta$ curve in the pigsty. In addition, $\eta$ initially increases, and then decreases in the range of $f$ from $1000\, \text{Hz}$ to $2000\, \text{Hz}$. Therefore, the linear variation law of $V-\eta$ & $SPL-\eta$ & $f-\eta$ provide scientific control method for the construction of green and efficient removal technology of particulate pollutants in the piggery.
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