Nonlinear Effect of Electrostatic Atomization with Multiple Nozzles

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Abstract. The interactions between the electric field electrodes of multi-nozzle electrostatic atomization system and atomized droplets space-charge effect make the charge quantity of atomized particle and the numbers of nozzles present a nonlinear effect. In this paper, the influence of the width of the electrodes, thickness of the electrode and shape of the electrode on spatial electric field distribution of the electrostatic atomizing system are analyzed. The results show that nonlinear effect can be improved obviously with the increase of the common edge width and height of the electrode; Compared with the quadrilateral structure, cylindrical electrode is more suitable for the application of multi-nozzle electrostatic atomization. Based on the theoretical analysis results, optimized design of electrostatic atomization structure is carried out and verified by experimental setup. The experimental results are consistent with the theoretical analysis results.

Introduction

Electrostatic atomization technology has been widely applied in industrial dedusting[1], micro/nano processing [2], atomizing combustion [3] and other fields. The electrostatic atomizing system based on induction charge usually uses the nozzle-electrode structure, liquid medium which flows through the nozzle is charged under the action of the electrostatic field and the droplets is broken down and atomized into small charged particles by overcoming the surface tension under coupling field of the electric field’s force and gravity [4]. The shapes of electrode, charged voltage, nozzle and structure of the electrode all have an important influence on electrostatic atomization. Especially under the joint action of multi-nozzle electrode structure, researchers found that the number and quantity of the electrostatic atomization particles showed a nonlinear trend with the number of nozzles which is caused by the interaction of the electric field between the adjacent electrodes and nozzle [5] and space charge effects the atomized charged particles [6]. On the basis of our previous research, the spatial electric field distribution of multi-nozzle electrode structure is theoretically analyzed, simulated and the influence rules of structural parameters on nonlinear phenomena are obtained which will provide a reference for the optimization design of the multi-nozzle electrostatic atomizing system.

Theoretical Analysis of Nonlinear Effect of Electrostatic Atomization with Multiple Nozzles

In electrostatic field, the droplet is subjected to the effect of static electric power to overcome the surface tension [7] and then split into a small droplet [8] and the charge amount of each small droplet cannot exceed the Rayleigh limit value:

\[ Q = 2\pi(2\varepsilon\gamma\frac{d}{2})\frac{1}{2} \]  \hspace{1cm} (1)

Here, $\varepsilon$ is the dielectric constant of the surrounding medium, $\gamma$ is the surface tension of the liquid
and Φd is the diameter of the spherical droplet. For single nozzle, the droplets are mainly affected by the action of static and surface tension [9]. The distribution of the electric field and force analysis are shown in figure 1 as an example of the quadrangular electrode nozzle structure.

As shown in figure 1(c), the force of electrostatic field for the droplet can be decomposed in many directions [10]. During the drop down process, the droplet is deformed and then is broken with the increase of time. The integral method can be used to force analysis and the force along with the positive direction of the X axis and the negative side can be expressed as F11 and F12 respectively.

\[
F_{11} = \frac{\pi}{2} \cos \beta \cdot E \cdot Q
\]  

\[
F_{12} = \frac{3\pi}{2} \cos \gamma \cdot E \cdot Q
\]  

By calculation it’s possible to know, if β=γ, then F11 and F12 are two quantities for the same size and opposite direction. Therefore, the force of droplets in horizontal direction is uniform.

As shown in figure 1(d), in the vertical plane as the droplets are subjected to a similar force before and after the rupture, the orthogonal decomposition method can be used to decompose the static power into F21 and F22 in which the resultant force parallel to the direction of the electrode is Fh1.

\[
F_{h1} = F_{21} \cdot \sin \alpha - F_{22} \cdot \sin \beta
\]  

When α=β, Fh is equal to 0, that means when the droplet is located at the center of the horizontal position of the electrode, the droplet's force on the horizontal plane is uniform. When the droplet is broken into n droplets in this state, the equation should be satisfied.

\[
V = \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} \frac{8}{3} \pi r_i^3
\]

Here, V is the unruptured droplet volume, Vi and ri are the radius and volume of small droplets respectively, i is the droplets serial number. The radius of all droplets at this time is made into an array, that is \{γ\[12\]}. 

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Figure 1. Force analysis of liquid drop of single nozzle.
In the multi-nozzle electrode structure, droplet is not only influenced by the electrode corresponding to the nozzle but also affected by the adjacent nozzles and electrodes. The distribution of electric field and force analysis are shown in figure 2.

As shown in figure 2(b), under certain condition of two nozzles, there is an interrelationship between two nozzles and electrode itself. As shown in figure 2(c), along with the direction of the X axis, the droplets are simultaneously subjected to the forces of their own electrodes and adjacent electrodes, which is set to be $F_3$ and in the negative direction of X axis, only the forces is produced by their own electrodes, it is set to be $F_4$. Now, $F_3$ and $F_4$ can be expressed as:

$$F_3 = F_{31} + F_{32} = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos \beta \times E \times Q + \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos \gamma \times E \times Q$$

$$F_4 = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos \alpha \times E \times Q$$

As shown in figure 2(d), the resultant force of droplets is parallel to the electrode in the vertical plane is $F_{h2}$.

$$F_{h2} = F_6 = \sin \alpha - F_{31} \times \sin \beta - F_{32} \times \sin (\beta + \gamma)$$

Calculation shows that the results of the equation (6) and equation (8) are not zero when $\alpha = \beta$. In the case of multiple nozzles, the force of droplets in the horizontal plane is not uniform. According to equation (5), the droplet radius array of atomized droplets can be obtained under this condition which is set to be $\gamma_{i2}$. Obviously, the variance of $\gamma_{i1}$ is lower than the variance of $\gamma_{i2}$. That means, if the flow rate is same, $V$ is also the same, then $\sum_{i=1}^{n} r_{i1} > \sum_{i=2}^{n} r_{i2}$.

Because of the droplet charged ($Q$) quantity in equation (1) is related to the radius of the droplet ($r$) after splitting, if the total amount of charged droplet is charged with uniform force denoted by $Q_1$ and total charged droplet is charged with non-uniform force denoted by $Q_2$, obviously there is $Q_1 \geq Q_2$. Therefore, when the number of nozzles is increased, number and amount of charged droplets in a single nozzle are decreased.

**Influence of Multi-Nozzle Electrode Structure Parameters on Nonlinear Effect**

**The Influence of Common Side Width on Nonlinear Effect**

Based on classical electromagnetic theory, the thickness of conductor is proportional to the degree of conductor’s obstruction to electrostatic field [11]. Taking dual nozzle grid electrode structure as the research object, the width of common edge of the grid electrode is adjusted in the range of 1 mm
-10 mm and the electric field distribution is simulated and analyzed. When the common side width is 10 mm, the result of electric field analysis is shown in figure 3.

![Figure 3. Distribution of electric field (when the width of common side is 10 mm).](image)

As shown in figure 3(b), the equipotential lines of 3700V and 3800 V are two closed ellipsoidal geometries but the equipotential line of 3900 V has turned into a closed curve. In this case, nonlinear effect has been improved but the influence of nonlinearity has not been eliminated. The potential value of the equipotential surface is presented in a single closed curve under the condition of $N<10$ which is shown in table 1.

<table>
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<tr>
<th>Width (mm)</th>
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<th>3</th>
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As shown in table 1, the potential of the potential line is increased as the increase of the common side width, that means the intensity of electric field interference from the adjacent electrode is getting lower and lower, which is helpful to improve the nonlinear effect.

**Influence of the Grid Electrode Thickness on the Nonlinear Effect**

According to the theory of electrostatic shielding, the greater degree of inclusion of conductor shell to the charged object, the smaller electrostatic field inside the conductor shell which is affected by external electrostatic field. According to the actual working conditions of the multi-nozzle electrostatic atomization system, study is explored on the multi nozzle structure of hollow rectangular electrode with the outer side length 10 mm and inner side length 8 mm, thickness $h_1$, common side width $h_2$. When $h_1 = 7$ mm, $h_2 = 1$ mm, the results are shown in figure 4.

As shown in figure 4(b), the equipotential line has begun to change two circles to two classes of ellipse at 3600 V and it has become a single closed curve when the potential is reached to 3800 V. Compared to figure 2(b), it is found that the potential line voltage of a single curve is raised, proving that the change of thickness can improve the nonlinear effect. On this basis, the electric field distribution of different combinations of $h_1$ and $h_2$ are studied and the results are shown in figure 5.
As shown in figure 5, closed equipotential line voltage is getting higher and higher with the increase of $h_1$ and $h_2$. When $h_1 = 10 \text{ mm}$ and $h_2 = 9 \text{ mm}$, the closed equipotential line is reached to 4956 V, indicating that the nonlinear phenomenon is very weak in this condition, but it always exists.

**Influence of the Electrode Shape on the Nonlinear Effect**

According to the theory of electrostatic field distribution, the distribution of the electrostatic field is affected by the curvature of the conductor that produces the electrostatic field. For the rectangular electrode described in the previous section, there is a point of different curvature in some part, as shown in figure 6.

![Figure 6. Section curvature analysis of rectangular electrode.](image)

According to the curvature formula $K = \left| \frac{\Delta S}{\Delta s} \right|$, $K_A = K_C = 0$. When $\Delta S$ is similar to zero, $K_B \to \infty$. Therefore, for rectangular electrodes distribution of electrostatic field is not uniform. To obtain uniform distributed electric field, the electrode with standard cross-sectional area is required. Based on the above analysis results, hollow cylinders are used as electrodes to encapsulate the nozzles. The electrical field distribution of the electrode structure is shown in figure 7.

![Figure 7. Electric field distribution of multi-nozzle cylindrical electrode.](image)
As shown in figure 7 (a), the purple part is the electrode which contains two hollow cylinder electrode. The outer diameter is 10 mm, inner diameter is 8 mm, height is 3 mm, thickness of common connection is h4, voltage is set to 5 kV, nozzle outer diameter is set to 1.5 mm, inner diameter is 1 mm and the length is 13 mm. When h3=2, h4=10, the electric field is shown in diagram 7(b), the coil from inside to outside is equal to the potential surface of 3.8kV- 4.8kV respectively. According to the distribution law of electric field, electric field around the two nozzles is all about 1.8 kv/mm. From the structure of electric field in figure 7(b), it can be seen that the equipotential surfaces of 3.8kV to 4.8kV are all closed, that means electrostatic fields of two nozzles are not affected by the electric field of adjacent electrodes. Combining data of figure 5, different combinations of h3 and h4 are simulated respectively and the results are shown in figure 8.

Figure 8. Influence of electrode thickness and common edge width on critical voltage of closed equipotential surface.

It is shown in figure 8 that the voltage of equal potential line is 5 kV when h3 is not less than 3 mm and h4 is not less than 7mm, which indicates that the electrostatic field between the two electrodes has no mutual influence at this time.

Experimental Verification

Four kinds of electrostatic atomization structures of single nozzle, double nozzle-grid electrode (h1=1, h2=1), double nozzle-hollow cylinder (h3=1, h3=1) and double nozzles-hollow cylinder (h3=4, h4=8) were tested. The results are shown in figure 9.

Figure 9. Experimental study on nonlinear effects of different electrode structures.

From figure 9 (a) & 9(b), it can be seen that the scattering angle of two nozzles is obviously smaller than the single nozzle. In figure 9(c), in case of h1=3 and h2=4 the scattering angle is slightly larger than that in figure 9 (b) due to use of the hollow cylindrical electrode. In the case of h1=h3 and h2=h4, scattering angle is almost same as the single nozzle scattering angle. In case of figure 9(d), droplets are hardly affected by the corresponding electrodes of another nozzle. For the different combinations of h1 and h2, h3 and h4, experimental results were tested respectively. The
mean scattering angles of two nozzles were analyzed and calculated on the basis of the experimental results. The results are shown in table 2 and table 3.

Table 2. Mean scattering angle of rectangular electrodes under different conditions.

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Table 3. Mean scattering angle of cylindrical electrodes under different conditions.

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It is visible from table 2 and table 3 that average scattering angle of the rectangular electrode is 45 degrees and is significantly less than 58 degree of the single nozzle. The scattering angle of cylindrical electrode at h3=3 and h4=7 is 52 degrees and mean scattering angle is 57 degrees at h3=4 and h4=8, which can be seen as same scattering angle as single nozzle when considering the error.

**Conclusion**

The force analysis of the droplets in multi-nozzle electrostatic atomization system is carried out and causes of the nonlinear effect are explained. The simulation and experimental research on factors affecting the electric field distribution of electrostatic atomizing system are also carried out. The results show that potential value of the closed potential line is getting higher and higher with the increase of common edge width and thickness of the electrode. It can be improved nonlinear effect of multi-nozzle structure and electrode curvature has an important influence on the distribution of electric field. Under the condition of height 4 mm and width 8 mm, the cylindrical electrode can be achieved same electrostatic atomization effect as the single nozzle. In the follow-up study, the number of nozzles can be further increased and spatial charge effect of nonlinear phenomena can be analyzed. On this basis, study of the multi-nozzle electrostatic atomization system miniaturization can be explored.

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**References**


