Simulations and experiments of the generation apparatus of the DC electric field with the space charge

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1 | INTRODUCTION

Direct current (DC) transmission technology has significant advantages in large-capacity and long-distance transmission; thus, it has been increasingly used to transfer electrical energy. However, the electromagnetic environment in the vicinity of high-voltage transmission lines causes public concern [1, 2]. Because of the presence of the corona discharge, the electromagnetic environment of high-voltage DC lines is complicated [3, 4]. One environmental factor is that the electric field is significantly influenced by space-charge contributions. Measurements and calculations of the corona space charge have been researched by researchers from many countries [5–8].

As a basic electromagnetic parameter of the electromagnetic environment of transmission lines, its important to improve the accuracy of measurement of the DC electric field strength. There are two main types of DC electric-field metres: field mills [9–14] and vibrating plate electric-field metres [15, 16]. To ensure the accuracy of measurement, an apparatus is required to calibrate the instruments. There are many calibration methods and types of calibration apparatus have been studied [17–21]. However, most types of calibration apparatus are the same as those provided in IEEE Standard 1227-1990 [22]. Two kinds of parallel plate systems can produce known electric fields separately: with and without a space charge. However, there is only a schematic diagram of the developed apparatus in the standard with no discussion about how to design them [22], and the influences of the structure parameters on the calibration apparatus are also not considered. In addition, the authors expounded the ion mobility under the voltage only in the range of 400–1600 V, but ion mobility under a lower and higher voltages was not given.

Based on the construction of a generation apparatus that can produce an electric field with space charges, a simulation model of the generation apparatus was built and the influence of the openings of different metal electrodes was calculated and analysed. Based on the simulation results, a generation apparatus was designed and developed, and ion mobility under different polarity modes was studied.

2 | SIMULATION AND ANALYSIS

2.1 | Apparatus and mathematical theory

A schematic diagram of the generation apparatus of an electric field with a space charge is shown in Figure 1 [23]. Copper
wires are used to generate ions. The ions are directed downward to the control electrode. Ions that are not collected on the control electrode continue downward to the high-voltage electrode of a parallel-plate system. The ions pass through the high-voltage electrode, and then travel a distance to the ground electrode and form the current density. An ammeter is used to measure the ion current. There are four electrically isolated current-sensing metal patches mounted on the ground electrode. Knowledge of the area of the patches then permits the calculation of the ion current density.

The calculation field is selected between the high-voltage electrode and the ground electrode. The field is full of space charges. Under the action of an electric field force, space charges migrate at a corresponding speed to form current. When the corona discharge is stable, the ion flow field can be assumed to be a steady-state field independent of time variables. At the same time, the space potential function is introduced:

\[
\nabla \cdot E = \frac{\rho}{\varepsilon_0} \tag{1}
\]

\[
J = \rho k E \tag{2}
\]

\[
\nabla \cdot J = 0 \tag{3}
\]

\[
E = -\nabla \varphi \tag{4}
\]

where \( E \) is the electric field intensity, \( \rho \) is the space charge and \( \varepsilon_0 \) is the vacuum dielectric constant, \( J \) is the ion current density, \( k \) is ionic mobility, and \( \varphi \) is the potential value.

The electric field between the parallel plates can be calculated by the formula:

\[
E = \left( \frac{E_0^2 + \frac{2Jz}{k\varepsilon_0}}{E_0} \right)^{1/2} \tag{5}
\]

where \( E_0 \) is the electric field at the high-voltage electrode and \( z = 0 \). The potentials at \( z = 0 \) and \( z = d \) shown in Figure 1 are \( V_T \) and 0, respectively. \( d \) is the distance from the high electrode to the ground electrode. Using Equation (4), the relation between \( E_0 \), \( k \), \( J \) can be determined:

\[
\frac{3J V_T}{k \varepsilon_0} = \left( \frac{E_0^2 + \frac{2Jz}{k\varepsilon_0}}{E_0} \right)^{3/2} - E_0^3 \tag{6}
\]

When the ion current density of the parallel plate electrode area is saturated with the space charge, electric field intensity \( E_0 \) at the high-voltage electrode is 0, so:

\[
E = \left( \frac{2Jz}{k\varepsilon_0} \right)^{1/2} \tag{7}
\]

and:

\[
k = \frac{8}{9} \frac{J_S}{\varepsilon_0} \frac{d^4}{V_T^2} \tag{8}
\]

where \( J_S \) is the saturated ion current density, when \( k \) is substituted into Equation (7):

\[
E = \frac{3V_T}{2d} \left( \frac{z}{d} \right)^{1/2} \tag{9}
\]

The electric field at the centre of the ground electrode is \( 1.5V_T/d \). The value of \( k \) depends on the measure of \( J_S \) for a specific \( V_T \) and can be determined by Equation (8).

### 2.2 Simulation of the calibration apparatus

The simulation is based on the combination of the electric field and the transfer of the dilute substances model. The two physical fields were coupled to simulate the electric field strength of the ion flow field in the check zone. Using Equations (1) and (4), the ion flow field after the corona of thin copper wires can be described by Poisson’s formula:

\[
\nabla^2 \varphi = -e \frac{n_p - n_n}{\varepsilon_0} \tag{10}
\]

where \( e \) is the basic electron charge. \( n_p \) is the number densities of positive ions, and \( n_n \) is the number densities of negative ions, respectively. The continuity equations of ion current are [24, 25]:

\[
\frac{\partial n_p}{\partial t} + \nabla \cdot \left( -\nabla \left( D_p \cdot n_p \right) + n_p u_+ \right) = -R n_p n_n \tag{11}
\]

\[
\frac{\partial n_n}{\partial t} + \nabla \cdot \left( -\nabla \left( D_n \cdot n_n \right) + n_n u_- \right) = -R n_p n_n \tag{12}
\]

where \( D_p \) and \( D_n \) are the positive and negative ion diffusion coefficients, respectively. \( R \) is the positive and negative ion recombination coefficient. \( u_+ \) and \( u_- \) are the positive and negative ion drift velocities, defined as:

\[
u_+ = k_+ E \tag{13}
\]

\[
u_- = k_- E \tag{14}
\]
where \( k_+ \) and \( k_- \) are positive and negative ion mobilities, respectively.

To express the basic equations as a convection-diffusion form, we expanded Equations (11) and (12) as:

\[
\frac{\partial n_+}{\partial t} + \nabla \cdot q_+ + u_+ \cdot \nabla n_+ = -n_+ \nabla \cdot u_+ - R_{n+}n_+ n_\text{\(n\)}
\]  
(15)

\[
q_+ = -D_+ \nabla n_+
\]

\[
\frac{\partial n_-}{\partial t} + \nabla \cdot q_- + u_- \cdot \nabla n_- = -n_- \nabla \cdot u_- - R_{n-}n_- n_\text{\(n\)}
\]  
(16)

\[
q_- = -D_- \nabla n_-
\]

where \( q_+ \) and \( q_- \) are the positive and negative ion diffusion mass fluxes, respectively. This indicates that the source terms of convection-diffusion equation contain two parts. One is contributed by the divergence of the drift velocity. The other is caused by the recombination of the positive and negative ions.

Substituting Equations (9), (10), (13) and (14) into (15) and (16), we get:

\[
\frac{\partial n_+}{\partial t} + \nabla \cdot q_+ + u_+ \cdot \nabla n_+ = -\frac{k_+ e}{\varepsilon_0} n_+ (n_+ - n_-)
\]  
(17)

\[- R_{n+} n_+ n_\text{\(n\)}

\[
\frac{\partial n_-}{\partial t} + \nabla \cdot q_- + u_- \cdot \nabla n_- = -\frac{k_- e}{\varepsilon_0} n_- (n_- - n_+)
\]  
(18)

\[- R_{n-} n_- n_\text{\(n\)}

The source terms of the convection-diffusion equation in the transfer of dilute materials are all expressed by dependent variables and known constants. The equation can be solved by the finite element method. When there is only a positive or negative unipolar source in the field, Equations (17) and (18) are: modified as:

\[
\frac{\partial n_+}{\partial t} + \nabla \cdot q_+ + u_+ \cdot \nabla n_+ = -\frac{k_+ e}{\varepsilon_0} n_+^2
\]  
(19)

\[
\frac{\partial n_-}{\partial t} + \nabla \cdot q_- + u_- \cdot \nabla n_- = -\frac{k_- e}{\varepsilon_0} n_-^2
\]  
(20)

It is obvious that there is only the divergence of the drift velocity in the field, not the recombination of positive and negative ions. The unipolar source was used to calibrate the probes in the simulation, the parameters setting of which are shown in Table 1. A diagram of the simulation model is showed in Figure 2. The distance between the corona wires and the control electrode is 0.05 m. The distance between the control electrode and the high-voltage electrode is 0.1 m. The distance of the parallel-plate system is 0.15 m. The radius of the three-layer plate is 1.4 m (0.7 m for the axisymmetric model), the diameter of the copper wire is 0.5 cm and the spacing of the copper wire is 5 cm, the openings of the control electrode is 2.5 cm, and the openings of the high-voltage electrode are 1.25 cm.

Based on the simulation model, the electric field and ion current density of the calculation path are calculated. The comparison results between the simulation values and theoretical values calculated by Equation (8) for the electric field strength and charge density shown in Figure 3. The simulation results are in good agreement with the theoretical results when the field is stabilised. Thus, the simulation model is effective and precise.

First, the influences of the spacing of the corona wires were calculated. Then, the simulation results showed that the electric field intensity distributions and the charge density were the same under different spacings of corona wires. Thus, the simulation results were displayed here. The influences of the openings of the control electrode on the distribution of the electric field and charge density are shown as Figure 4. The error of the electric field and of charge density at \( z = 0.15 \) are shown in Table 2. The error is small (not more than 1.2%), so the openings in the control electrode have almost no effect on the electric field intensity and the charge density near the centre of the ground electrode (\( z = 0.15 \)). There is only a little difference near the high-voltage electrode (\( z = 0 \)).

| Symbol | Quantity | Value |
|--------|----------|-------|
| \( k_+ \) | Positive ion mobility | \( 1.5 \times 10^{-4} \) m²/(V·s) |
| \( k_- \) | Negative ion mobility | \( 1.7 \times 10^{-4} \) m²/(V·s) |
| \( D_+ \) | Positive ion diffusion coefficient | \( 3.8 \times 10^{-6} \) m²/s |
| \( D_- \) | Negative ion diffusion coefficient | \( 4.2 \times 10^{-6} \) m²/s |
| \( R \) | Ion recombination rate | \( 1.602 \times 10^{-30} \) C |
| \( \varepsilon_0 \) | Vacuum dielectric constant | \( 8.85 \times 10^{-12} \) F/m |
| \( E \) | Elementary charge | \( 1.602 \times 10^{-19} \) C |

**Table 1** Calculation parameters of simulation model.

**Figure 2** Diagram of simulation model.
The influence of openings in the high-voltage electrode on the distribution of the electric field and charge density are shown in Figure 5. The errors for the electric field and the charge density at $z = 0.15$ are shown in Table 3. When the opening size is 0.0125 m, the error is not more than 1%. The openings of the high-voltage electrode have a great effect on the distribution of electric field strength and charge density. When the opening is 0.0125, the error value is not more than 1%. This is in good agreement with the theoretical value. If the opening is further enlarged (when the opening size is 3.75 cm), the electric field strength will greatly increase near the high-voltage electrode and the charge density distribution will also increase; the error rises to 189%. The reason is the existence of the jet phenomenon. In other words, because the screen is not the ideal plate, a fountain will be produced when the ions pass through the high-voltage electrode [26, 27], and then the ions are together. Therefore, the electric field and charge density change greatly. In addition, simulation values tend to be close to the theoretical value with a decrease in the opening size of the high-voltage electrode. Thus, the opening size of the high-voltage electrode should be smaller, and the best value should not be more than 1.25 cm based on the simulation results.

### Table 2

| Opening size (m) | Error of $E$ (%) | Error of $\rho$ (%) |
|-----------------|-----------------|-------------------|
| 0.025           | -0.23%          | 0.15%             |
| 0.050           | 0.45%           | 0.32%             |
| 0.075           | 0.90%           | 0.55%             |
| 0.100           | 1.13%           | 0.60%             |

### 3 | APPARATUS DESIGN AND EXPERIMENTAL ANALYSIS

#### 3.1 | Parameters of calibration apparatus

A designed and developed calibration apparatus is shown as Figure 6. Ions generated by 20 constantan wires with the diameter of 0.091 mm are directed downward 8 cm to the control electrode. Regarding the influence of the size of the
metal plates [28], the control electrode consists of a stainless-steel grid mounted on a 1.4 × 1.4 m steel frame. The openings are 1.2 × 1.2 cm. The high-voltage electrode is a copper window screen with openings of approximately 0.12 × 0.12 cm. The metal mesh is also fixed on a 1.4 × 1.4 m steel frame. It was stretched to provide a nearly flat surface. The ground electrode consists of aluminium plates 0.2 cm thick mounted on a 1.4 × 1.4 m steel frame. Eight current sensing elements are mounted on the ground electrode to measure the ion current density. The areas of the current sensing elements are approximately 40 cm².

To limit the induced voltage of the parallel plates, the resistors should be parallel between the different metal plates. Thus, the choice of the resistance of $R_1$ and $R_2$ (Figure 1) was studied. The experimental results showed that the resistance value of $R_1$ mainly affects the induced voltage of the control electrode. Because the control voltage applied on the control electrode is relatively high, it has little need for resistance selection. However, induced voltage on the high-voltage electrode is strongly influenced by the resistance of $R_2$. The test results show that the induced voltage is relatively larger with the large resistance of $R_2$. To reduce the influence of the induced voltage, $R_2$ should have a smaller resistance. However, it should not be too small. If the resistance of $R_2$ is too small, the DC high-voltage cannot be applied on the high-voltage electrode because the leakage current is too large. According to the experimental results, when the field strength below 1 kV/m, the value of $R_2$ is about 100 kΩ; when the electric field strength is in the range 1~15 kV/m, the recommended value of $R_2$ is about 1 MΩ. When the field strength exceeds 15 kV/m, the chosen value of $R_2$ is 5 MΩ.

### 3.2 Experimental result of the ion mobility

To measure ion mobility, tests were conducted by increasing the control voltage of control electrode $V'_2$ while keeping $\Delta V = V'_{1} - V'_2$ nearly constant. ($V'_1$ is the voltage applied on the corona wires.) The degree of corona discharge depends on voltage difference $\Delta V$. The influence of $\Delta V$ on the space-charge-limit current has been studied. From the experimental results, some conclusions can be made: When the electric field strength is small, voltage difference $\Delta V$ should be small and the space-charge-limit current will be relatively stable; when the electric field strength is large, voltage difference $\Delta V$ should be increased so that the space-charge-limit current will reach the saturation state quickly. However, because of the insulating strength between the different electrodes, the voltage difference cannot
increase without a limit. The value of the voltage difference $\Delta V$ is 25 kV here.

The space-charge-limit current for the positive mode and negative mode as a function of the control voltage applied on the control electrode is shown in Figures 7 and 8, respectively. The lowest test voltage applied on the high voltage electrode is 50 V. The space-charge-limit current density decreases with increases in control voltage $V_T$, and the current density shows a significant saturation trend.

According to the saturated current density, ion mobility as a function of the voltage applied on the high-voltage electrode is calculated. Ion mobility for the positive and negative modes is shown as Figures 9 and 10, respectively. Ion mobility is gradually reduced with an increase in voltage $V_T$ applied on the high electrode. In this study, the minimum voltage of $V_T$ can be lowered to 50 V at the positive mode, and its ion mobility is $4.77 \times 10^{-4}$ m$^2$/V s. The ion mobility of the negative mode is obviously larger than that of the positive mode. The main reason is that the negative charge is mainly electrons and the positive charge is mainly positive ions, but the mass of the positive ions is much larger than that of electrons, so the mobility is relatively small [29–31]. The experimental results agree with the conclusion in the literature [23, 32].

The mathematical expression of the fitting curve in Figures 9 and 10 can be written as:

$$k_+ = \left(3.496 \times e^{-V_T/87.578} + 1.513\right) \times 10^{-4}$$  \hspace{1cm} (21)

$$k_- = \left(3.641 \times e^{V_T/154.092} + 1.838\right) \times 10^{-4}$$  \hspace{1cm} (22)

where $k_+$ and $k_-$ is the ion mobility of the positive and negative modes, and $V_T$ is the voltage applied on the high voltage electrode. The value of $R^2$ is 0.9888 and 0.9467, respectively.

The fitting curve of ion mobility shows that ion mobility tends to be saturated with an increase in the voltage of the high-voltage electrode. The saturated values of ion mobility of the negative and positive modes are $1.513 \times 10^{-4}$ m$^2$/V s and $1.838 \times 10^{-4}$ m$^2$/V s, respectively. Although the fitted value

![Figure 7](image7.png)  \hspace{1cm} **Figure 7**  \hspace{1cm} Space-charge-limit current density under the positive mode

![Figure 8](image8.png)  \hspace{1cm} **Figure 8**  \hspace{1cm} Space-charge-limit current density under the negative mode

![Figure 9](image9.png)  \hspace{1cm} **Figure 9**  \hspace{1cm} Ion mobility under the positive mode

![Figure 10](image10.png)  \hspace{1cm} **Figure 10**  \hspace{1cm} Ion mobility under the negative mode
under high field strength is larger than the measured value, the main reason is that the measured saturation current is relatively small. Figure 8 shows that the space-charge-limit current density for the $V_T = 1500$ V did not reach a full saturation state. However, a reason for the saturated trend of the ion mobility may be that the voltage difference between the corona wires between the control electrodes is relatively small, so the corona discharge cannot support enough ions for the check zone. For our generation apparatus, the phenomenon of breakdown between electrodes occurred during the experiment. Thus, another reason may be that the control voltage is constricted by the insulation strength between the control electrode and the high-voltage electrode. Therefore, the control voltage of the control electrode cannot increase in an unlimited manner, and the electric field force cannot draw more ions into the check zone.

Moreover, the saturation current density was tested when $V_T$ was greater than 2 kV. The experimental results showed that control voltage $V_2$ must be increased higher with an increase in voltage $V_T$, and then the space-charge-limit current can be reach the saturation state. For example, when the value of $V_T$ is up to 6 kV, the ion current still cannot reach the space-charge-limit current when control voltage $V_2$ increases to near 15 kV. However, the control voltage cannot be increased because of the limit of the insulation strength between the control electrode and the high-voltage electrode. Thus, the ion mobility of the high voltage cannot get through the experiments. However, we think that the ion mobility can be obtained through the Equations (21) and (22) based on the analysis of the reasons for saturation.

4 | CONCLUSION

A simulation model of the calibration apparatus generating an electric field with a space charge was built. The simulation results showed that openings of the high-voltage electrode have a great influence on the distribution of the electric field and ion current density at the calibration position. The size of openings of the high-voltage electrode should not exceed 1.25 cm. A calibration apparatus was designed and developed, and ion mobility was tested. The experimental results showed that ion mobility of the negative mode was bigger than that of the positive mode. Ion mobility tends to be saturated when the electric field reaches a certain critical value. The prediction formulas of ion mobility were proposed for positive and negative charges, which can be used to forecast ion mobility in a high electric field.

ACKNOWLEDGEMENT
The authors acknowledge the Science and Technology Project of the State Grid Corporation of China (No. 5200-201955075A-0-0-00).

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How to cite this article: Wang, Y., Zhang, J., Gan, Z., Xu, J.: Simulations and experiments of the generation apparatus of the DC electric field with the space charge. High Voltage. 1–8 (2021). https://doi.org/10.1049/hve2.12099