In-tube transport of ions for charge neutralization

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Abstract. This paper is a consideration of the tube transport of ions used in a high-frequency corona ionizer, with emphasis on how the positive and negative ions can be transported in a tube without significant losses. We developed a self-consistent fluid model using continuity equations of positive and negative ion densities and Poisson’s equation to solve the ion flow in the tube. The simulation using the model showed that the quasi-neutralized charge distribution created by positive and negative ions, which is achieved at high frequency, can reduce the radial electric field in the tube, resulting in a lower loss of ions at the tube wall, while, at the commercial frequency, such a charge distribution cannot be created.

1. Introduction
An ionizer of Shishido Electrostatics optionally uses a tube of 4 mm in inner diameter and several tens of centimeters in length to transport ions, which is advantageous in local charge neutralization, e.g., the charge neutralization in a narrow space surrounded with the earth potential. The ionizer uses a high-frequency corona discharge of 35 kHz and compressed airflow of less than 0.5 MPa (absolute pressure: 0.6 MPa) [1]. The characteristics regarding tube transport are as follows [2, 3]:
- Corona discharge at the commercial frequency is ineffective for tube transport;
- High frequency for the corona discharge is required for effective charge neutralization;
- There is no dependence on the conductivity of the tube.

In this paper, we will show how ions can be transported in a tube at high frequency by using a computer simulation.

2. Model
The framework of the model is the same as one used previously [4] in that it solves the flow of positive and negative ions by a set of equations of continuity of ion densities and Poisson’s as follows:

\[ \frac{\partial n_p}{\partial t} + \nabla \cdot (n_p v_p) - D_p \nabla^2 n_p = -\beta n_p n_n, \]  

\[ \frac{\partial n_n}{\partial t} + \nabla \cdot (n_n v_n) - D_n \nabla^2 n_n = -\beta n_p n_n, \]  

\[ \nabla^2 \phi = -\varepsilon (n_p - n_n) / \varepsilon_0, \]  

\[ E = -\nabla \phi. \]
where \( n_p \) and \( n_n \) are the positive and negative ion densities, \( \mathbf{v}_p = \mathbf{w}_p + \mathbf{v}_a \), \( \mathbf{v}_n = \mathbf{w}_n + \mathbf{v}_a \). Here, \( \mathbf{w}_p \) and \( \mathbf{w}_n \) are the corresponding drift velocities proportional to electric field \( \mathbf{E} \), and \( \mathbf{v}_a \) is the airflow velocity. The symbols \( D \) and \( \beta \) denote the diffusion and ion-ion recombination coefficients, and \( \phi, \varepsilon_0, \) and \( c \) are the potential, the permittivity of free space, and the electron charge, respectively. We use the drift velocities for positive and negative ions and the recombination coefficient in air given by [5] and the diffusion coefficients in [6]. To solve equations (1) and (2), the FCT scheme [7, 8] with a dynamic time-step, which satisfies the CFL condition, is used, and the SOR algorithm is used to solve equation (3).

To model the tube transport of ions, we use 2D cylindrical coordinates \((r, z)\) with the following boundary conditions: zero ion density gradients and zero electric field normal to the boundary are assumed at the axis and outlet \((z = 10 \text{ cm})\) of the tube; the potential of the outer of the tube wall at \( r = 6 \text{ mm} \) is zero; zero ion densities at the tube wall are assumed; for a non-conductive tube, the continuity of currents normal to the tube wall, which involves the displacement current by the surface charge by ions reached the wall as well, is employed to obtain the wall potentials; for a conductive tube, a zero potential is assumed at the wall; instead of the calculation for the charge of positive ions and, at \( r = 0 \), voltage, \( \phi \) is derived from a model of a corona ion source [4] based on Raizer’s deviation of the corona current [9] using Peek’s empirical formula for the corona inception field, \( E_c = 31.0 \times 10^3 (1 + 0.0308/\sqrt{r_0}) \), and Townsend equation of the corona current, \( i = \frac{8\pi\mu_0}{R^2\ln(R/r_0)} V (V - V_c) \) \((\mu: \text{mobility of ions})\), and the form of the distribution is derived from the Warburg distribution for the current density, where \( V_c (= E_c r_0 \ln (R/r_0)) \) is the corona inception voltage, \( r_0 (= 35 \text{ mm}) \) and \( R (= 2 \text{ mm}) \) are the inner and outer radii of the corona electrodes, \( m = 4.82 \) for positive ions and \( m = 4.65 \) for negative ions, the exponent 3 is derived from the ratio of the \( z \)-component of the Laplacian field to that at \( r = 0 \), \( E_z(r)/E_z(0) \propto \cos^3(\arctan r/d) \), in a point-to-plane configuration, \( d (= 1 \text{ cm}) \) is the distance between the tip of the needle corona electrode of the ionizer and the tube inlet, and \( V \) is the applied voltage for the corona discharge, \( V = V_0 \cos(2\pi ft), V_0 = 2\sqrt{2} \text{ kV}, \) respectively. Here, at \( V > 0 \), \( n(r) \) corresponds to the density of positive ions and, at \( V < 0 \), \( n(r) \) corresponds to that of negative ions; the potential at \( z = 0 \) and \( r < R \) assumed to be governed by \( \partial^2 \phi/\partial r^2 + r^{-1}\partial \phi/\partial r = -\varepsilon(n_p - n_n)/\varepsilon_0 \).

To numerically investigate the characteristics listed in section 1, the frequencies of \( f = 50 \) Hz and 35 kHz are used. In addition, conductive and non-conductive (with a dielectric constant of 2.1) tubes are compared to investigate the effect of the conductivity of tube material, i.e., the effect of the charging of the tube wall, which may retard the motion of ions with the same polarity of the wall charging toward the wall like plasma sheath; the effect is expected to be insignificant because the difference between the drift velocities of positive and negative ions is not large, and, in practice, the characteristics of the ionizer demonstrate the point.

A laminar airflow, \( v_a = v_{a0} (1 - v^2/R^2) \), is assumed for the compressed air, and the airflow velocities of \( v_{a0} = 30 \) and 50 m/s at \( r = 0 \) are chosen because the velocities of approximately 10 to 50 m/s at the range of the compressed pressures used in the ionizer were reduced from the values measured with a flow-meter.

3. Results and discussion

As shown in figure 1, at the high frequency of 35 kHz, the density distributions of positive and negative ions are almost identical. Such distributions lead to the quasi-neutralization of the charges of positive and negative ions in a tube. This significantly decreased the radial electric fields, resulting in a great decrease in the loss of ions at the tube wall (table 1). It necessarily
Figure 1. Density distributions of positive and negative ions in an insulating tube at the steady state for $f = 35$ kHz and $v_{a0} = 30$ m/s. The unit of the values of contour curves is in m$^{-3}$.

Table 1. Ratios of ions discharged from the tube to incoming ones and ratios of ion losses at the tube wall and by ion-ion recombination to total ones at the steady state.

| Frequency | Airflow $v_{a0}$ m/s | Tube material | Ratio of ions discharged % | Loss % |
|-----------|----------------------|---------------|----------------------------|--------|
|           |                      |               | Positive ions | Negative ions | Wall | Recombination |
| 50 Hz     | 30                   | Insulating    | 2.78          | 3.38          | 99.9 | 0.05          |
| 50 Hz     | 30                   | Conductive    | 2.95          | 3.57          | 99.9 | 0.07          |
| 50 Hz     | 50                   | Insulating    | 3.77          | 4.59          | 99.9 | 0.004         |
| 50 Hz     | 50                   | Conductive    | 3.96          | 4.81          | 99.9 | 0.008         |
| 35 kHz    | 30                   | Insulating    | 83.3          | 89.7          | 24.5 | 75.5          |
| 35 kHz    | 30                   | Conductive    | 75.9          | 81.8          | 17.3 | 82.7          |
| 35 kHz    | 50                   | Insulating    | 89.0          | 95.8          | 23.7 | 76.3          |
| 35 kHz    | 50                   | Conductive    | 87.3          | 86.6          | 17.4 | 82.6          |

caused an increase in the loss by the ion-ion recombination, but it was not very large. On the other hand, at the commercial frequency, non-quasi-neutralization was given because of the longer interval between the positive and negative ions alternatively entering the tube, as shown in figure 2, which resulted in a significant loss of ions at the wall. As shown in table 1, no significant effect of the conductivity of tube material was observed; however, using an insulating tube may be somewhat advantageous when the distributions are quasi-neutralized. A faster airflow is also somewhat advantageous because of the shorter residence time in the tube, which decreases the absolute number of losses.
Figure 2. Density distributions of positive and negative ions in an insulating tube at the steady state for $f = 50$ Hz and $v_{a0} = 30$ m/s.

4. Conclusion
The results of the modeling indicated that the quasi-neutralization of positive and negative ions in a tube, given at higher frequencies for the corona discharge, is of importance for the effective tube transport of ions and that the transport is almost independent of the conductivity of the tube material, which can explain the characteristics of the real ionizer.

Acknowledgments
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