An Estimation for Relaxation Characteristics of an Ionizer Ion Cloud Density Transferred through a Pipe via Hyperbolic Law

Yoshinari Fukada, Takashi Yasukawa, and Kyoko Yatsuzuka

Abstract—**In an ionizer to eliminate the electrostatic charge, Corona discharge is widely used. The ions generated by DC or AC discharge are often carried through a pipe or a tube toward the vicinity of the object. During transferring the ions it is well known that the ion density decreases with the traveling distance, however, the details of the mechanism is not clarified yet, because of the difficulty of the transferred charge measurement. We have investigated and reported about the measurement of the transferred ion density by a Faraday cage directly connected to an ionizer. In this report the experimental results of the relaxation characteristics of ion density transferred through a pipe by changing the length of the pipe between the ionizer and the Faraday cage. For DC corona discharge, the dependency of the ion current on the pipe length shows very good agreement with the estimation via hyperbolic law. For AC corona discharge, the relationship between the charge amount transferred per second and the traveling distance agreed with the estimation very well. At the last, the average flow velocity is driven from the hyperbolic law. The velocity calculated via hyperbolic law meets with the value from another experiments.**

Index Terms—**Ionization, Ions, Corona, Air transportation**

I. INTRODUCTION

In recent industries, especially such as in the semiconductor manufacturing production, the hard disk drive or liquid crystal display manufacturers, the monitoring and eliminating electrostatic charge is getting more and more important matter. The thinner pattern is used, the weaker the manufactured devices become for the electrostatic phenomena. The number of serious problems by low electrostatic electrification and discharge is growing. Such the unwanted charges are usually eliminated by using the charges of opposite polarity, generated in an ionizer. Corona discharge is widely used to generate charges in atmosphere in an ionizer. A DC or AC corona discharge is employed to generate the ions. The ions generated in an ionizer are often carried through a pipe or a tube toward the vicinity of the object by an air flow.

For DC corona, a pair of electrodes is needed, and the ions can be widely spread. For AC corona, it can generate positive and negative ions alternatively by one electrode. Thus, which corona, DC or AC, should be employed is depend on the situation. Now an ionizer using high frequency AC corona discharge becomes widely used, because of its high performance of electrostatic electrified elimination [1]-[3]. The most general evaluation method of the ionizer is so called a charged plate monitor (CPM) [4]. There is a standard of the evaluation method to determine the specification of an apparatus and a measuring procedure. In the measurement for a high frequency AC corona discharge ionizer, however, a CPM has disadvantage because of the induced current from the power supply or other noise source and its low frequency characteristics.

Thus we set our aim to establish the new evaluation method of the AC corona discharge ionizer. The ion transfer characteristics are examined in the nozzle type ionizer with compressed air for a DC or AC corona discharge. A Faraday cage is utilized for measurement of the transferred ions [5].

Using a faraday cage enable to avoid the problems of the induced current from power supply or the other noise source. This Faraday cage can collect the whole transferred ions and the relations between the ion density transferred through a pipe and the length of the pipe are measured. In this report the experimental results of the ion density transferred through a pipe for a DC or AC corona discharge ionizer and theoretically estimations are compared.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the experimental apparatus is shown in Fig. 1. A Faraday cage is connected directly to an ionizer output nozzle via a very short connecting pipe. This ionizer nozzle is a part of a blower type ionizer of Koganei Co. The ionizer has a needle electrode and pressurized air is blew in. The ions produced inside the nozzle are blown into the Faraday cage directly and entirely. The inner cylindrical container of the Faraday cage is connected to an oscilloscope or electrometer to measure the transferred ion current. We called the current as the ion current. Transferred charge amount is calculated from an ion current and the discharge duration time, called as the ion duration time.

In addition, the distance between the ionizer and the Faraday cage is varied by changing the connecting metal pipe of the

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different length, and the relations of the transferred charge density and the ion traveling distance are obtained.

III. RESULTS

A. DC corona discharge ionizer

The dependence of the ion current on the distance *d* of 50 to 500 mm is shown in Fig. 2(a) and (b). The discharge voltage is DC 3.5, 4 and 4.5kV, compressed air flow rate is 120L/min (air pressure: 0.18MPa). The ion current is estimated from the measured value of the inner container voltage by the oscilloscope, divided by the input resistance 1MΩ.

The longer traveling distance is, the less ion current is. Even the applied voltage changed, the ion current-pipe length characteristics hardly changed. This results agrees with the previous results [5]. The positive ion current is higher than the negative one.

B. AC corona discharge ionizer

Typical waveforms of the applied voltage and the ion currents, at *d*=100, 300, 500mm, for the sinusoidal AC corona discharge are shown in Fig. 3. The discharge voltage was set at the 9kV peak-to-peak voltage and the air flow rate at 120L/min (air pressure of 0.18MPa), and frequencies at 1Hz(Fig. 3(a)), 10Hz (Fig. 3(b)) and 100Hz (Fig. 3(c)). At the 9 kVp-p the corona discharge is stable at any frequencies.

The waveforms of Fig. 3 are averaged of 100 times each. The positive and negative ions are collected by the Faraday cage, during the positive and negative half-cycles of the waveforms in Fig.3, respectively.

The ion current is appeared when the corona is onset and extinguished when the applied voltage becomes below the corona onset voltage. The waveform of ion current, thus, is a square like waveform. When the frequency of the applied voltage is 1Hz, the magnitudes and widths of the ion currents are the same as both polarities.

The ion current decreases with increase of the traveling distance. At 1Hz, corona on-set and off-set thresholds are almost the same values. At 10, 100Hz, however, these thresholds are impossible to be measured, because of the phase difference of the ion current by the traveling distance. As for the width of the ion current waveform, means of the ion current duration time, it doesn't change with the traveling time at 1 and 10 Hz, though at 100Hz it is increasing slightly.

The ions current, the ion duration time and the charge amount of transferred ions are calculated from the waveform as shown in Fig. 4. The ion current is the average value during the ion current duration. The charge amount is calculated as the hatched area, multiplying the ion current and the ion duration time. The dependencies of ion current, the ion duration time and the charge amount of transferred ions on the traveling distance *d* are shown in Fig. 5~7, respectively. Fig. 5 shows that the ion current decreases with the traveling distance. Although the ion current does not change, there is an order of 1Hz > 10Hz > 100Hz in frequency. The positive ion current tends to be higher than the negative one.

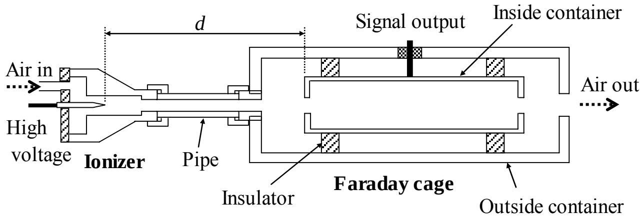
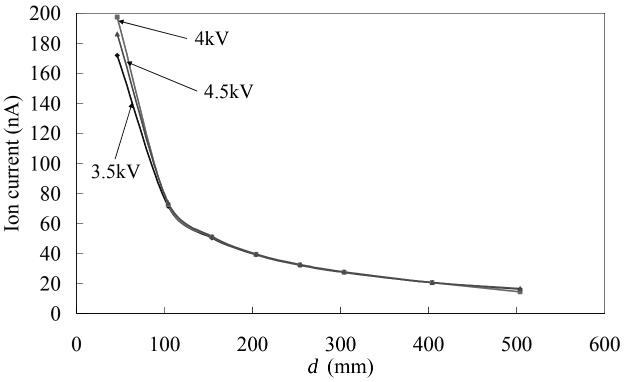
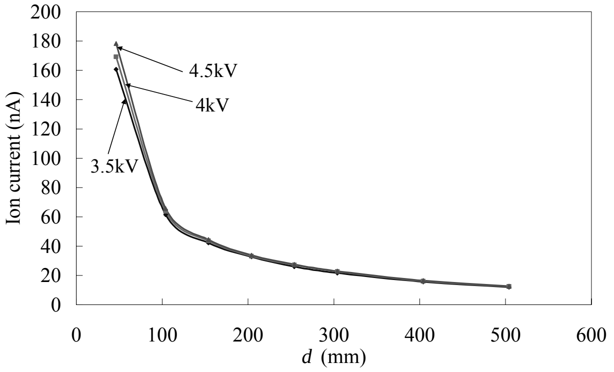


Fig. 1. Experimental apparatus



(a) Positive ion

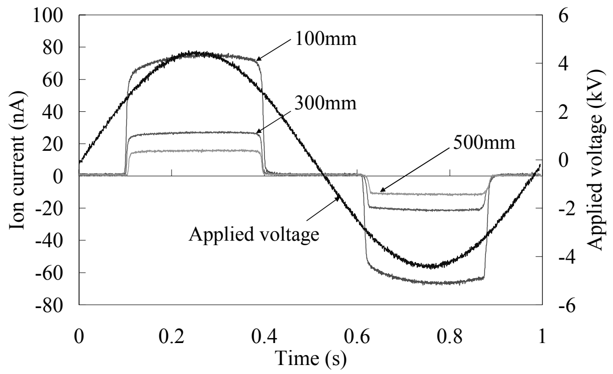


(b) Negative ion

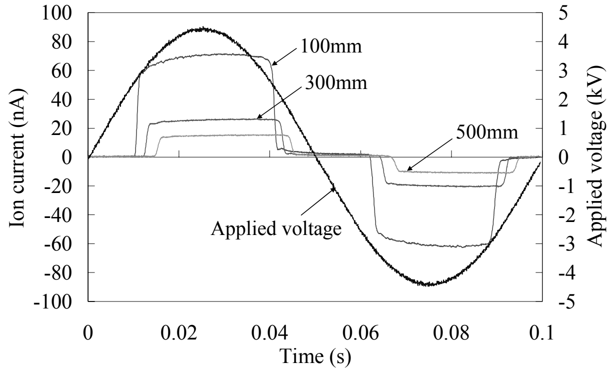
Fig. 2. Dependency of ion current on traveling distance.

Fig. 6 shows the dependency of the ion duration time per 1 second on the traveling distance at different discharge frequency. In other word, in the case of 10, 100Hz, the ion duration time for one waveform is only 10, 1% of measured at 1Hz, respectively, but the total durations in 1 second give the total time of ion current holding time in one second. At 1, 10Hz, the ion duration time per 1 second is constant with the traveling distance. At 100Hz, however, it increases with the traveling distance, expect for the negative ion on *d*=50mm. The ion duration time per 1 second lays in order of 100Hz > 10Hz > 1Hz in frequency. The positive ion duration time is longer than the negative one.

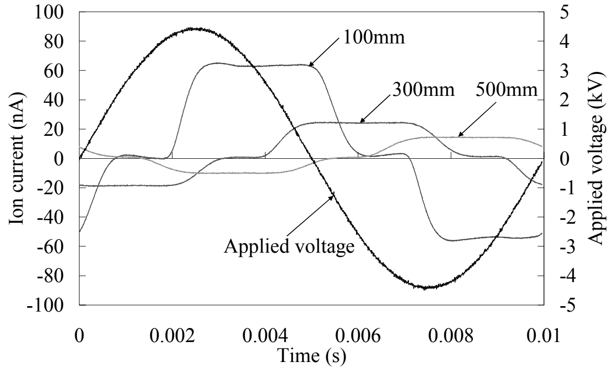
Fig. 7 shows the dependency of the charge amount per 1 second on the traveling distance at different discharge frequency. As the period is not the same through the all frequencies of the discharge applied voltage, again, the charge amount is normalized in one second. The normalized charge amount decreases with the traveling distance. Those value are the same at frequency (1Hz 10Hz 100Hz). The positive charge amount is larger than the negative one.



(a) Frequency of 1Hz



(b) Frequency of 10Hz



(c) frequency of 100Hz

Fig. 3. Measured configuration wave shape.

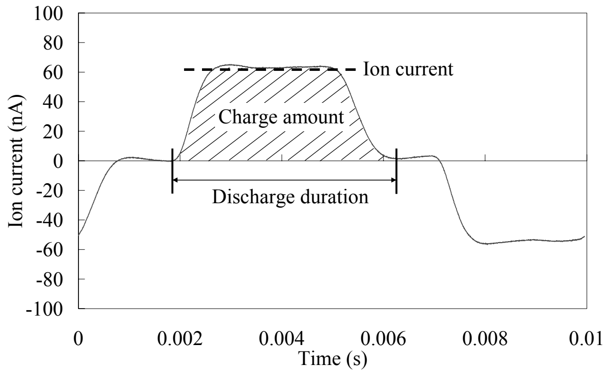
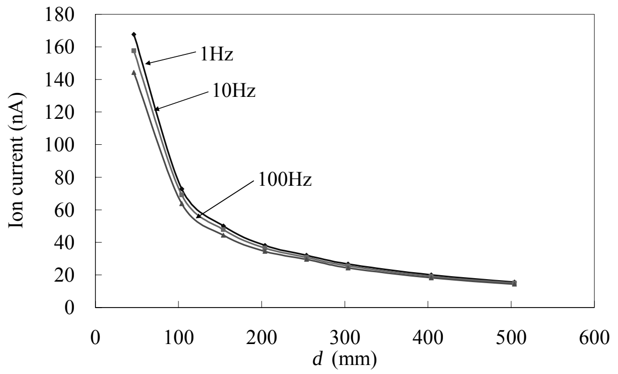
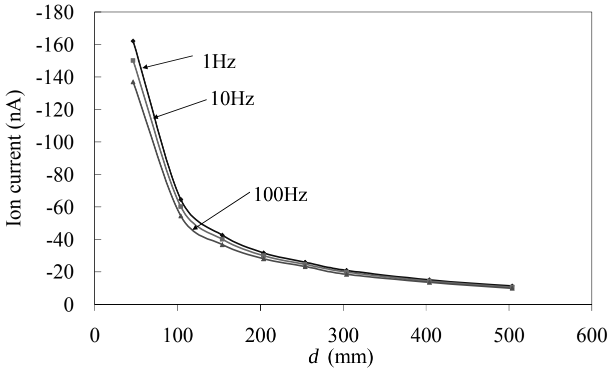


Fig. 4. Method of measurement.

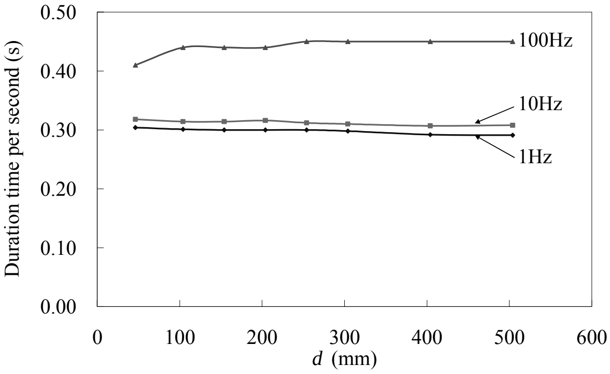


(a) Positive ion

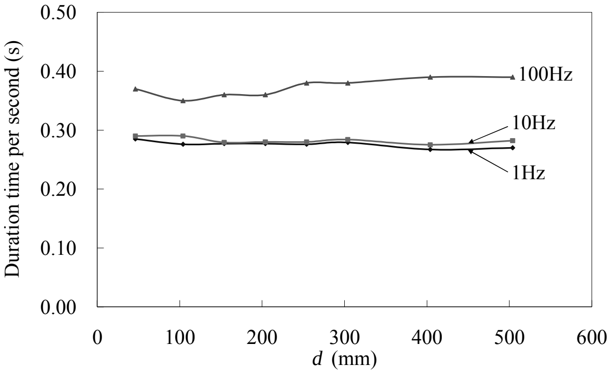


(b) Negative ion

Fig. 5. Dependency of ion current on traveling distance.



(a) Positive ion



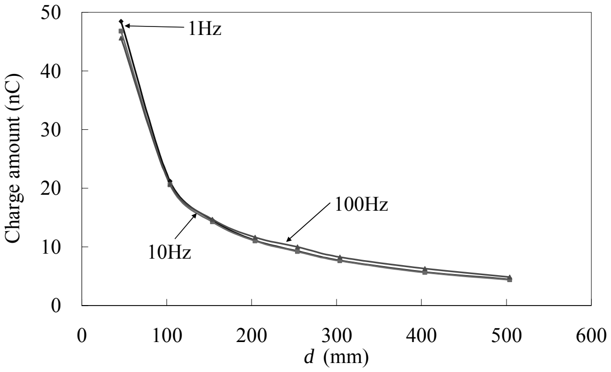
(b) Negative ion

Fig. 6. Dependency of duration time per second on traveling distance.

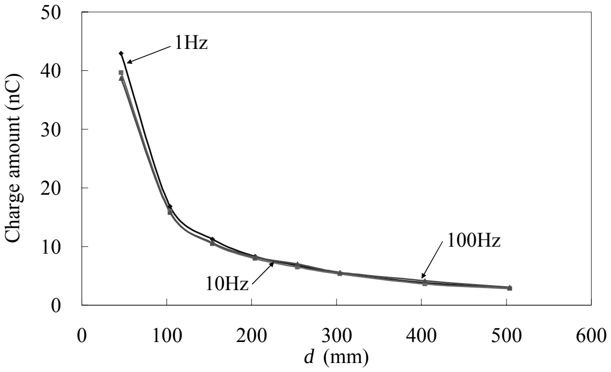
IV. DISCUSSIONS

A. Estimation of average flow velocity

An average velocity of ions is estimated from the phase difference between the applied voltage and the ion current waveform and the traveling distance of ions at 100Hz (Fig. 3(c)). The phase difference is calculated from the time difference between the middle points of two waveforms for different traveling distances. The middle points are determined at the half wave height of each waveform (Fig. 8). The average ion velocities determined from traveling distance of 100 and 300mm, and of 300 and 500mm are listed in Table 1. The average flow velocity estimated from the traveling distance becomes about 91.5m/s.



(a) Positive ion



(b) Negative ion

Fig. 7. Dependency of charge amount per second on traveling distance.

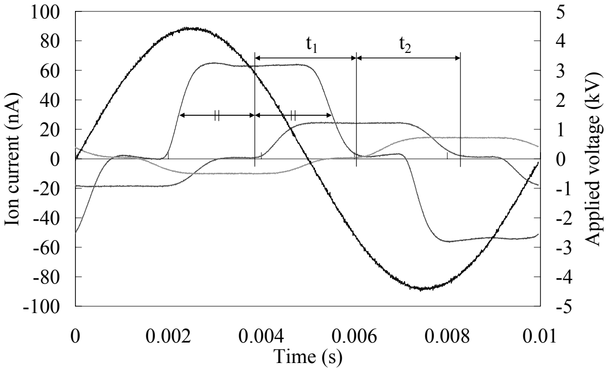


Fig. 8. Measurement of the phase difference.

TABLE I

THE PHASE DIFFERENCE AND ION VOLOCITY

	Phase difference (sec)	Velocity (m/sec)
t_1	0.00217	92.2
t_2	0.00230	87.1

B. Relaxations of transferred ion density via hyperbolic law

The relaxation characteristics of the ion density of a charge cloud generated by a DC corona discharge will be discussed here by the hyperbolic law.

Maxwell's law and constitution equations are written as,

$$\nabla \cdot \boldsymbol{D} = \rho, \tag{1}$$

$$\nabla \cdot \boldsymbol{J} + \frac{\partial \rho}{\partial t} = 0, \tag{2}$$

$$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E}, \tag{3}$$

$$\boldsymbol{J} = \rho \mu \boldsymbol{E}, \tag{4}$$

where $\boldsymbol{D}$ is the electric flux density, $\boldsymbol{J}$ is the current density, ρ is the charge density, $\boldsymbol{E}$ is the electric field, ε_0 is the permittivity in the free space and μ is the mobility of positive or negative ions, respectively. The density of transferred ions through a pipe, ρ, is driven from Eq. (1)~(4) [6], as

$$\rho = \frac{\rho_0}{1 + t/\tau}, \tag{5}$$

$$\tau = \frac{\varepsilon}{\rho_0 \mu}, \tag{6}$$

where ρ_0 is the initial charge density. The initial charge density should be the value at the connecting point of the ionizer and the Faraday cage, in our case, d=50mm, however, this is impossible to be measured experimentally. Thus, the initial charge density is estimated for the ion current. In other word, the initial charge density is estimated by dividing the ion current per one second by the volume of the ion cloud transferred through the pipe per one second.

At the positive DC 4.5 kV applied voltage, the charge amount per one second was

$$Q = 186.3 \times 10^{-9} \times 1 = 186.3 \times 10^{-9}\,\mathrm{C}. \tag{7}$$

As the average flow velocity is 91.5m/s, as described in Section 4A, and the inner diameter of the pipe is 5mm, those makes the ion cloud volume to pass through for one second, V,

$$V = \pi \times \left(\frac{5}{2} \times 10^{-3} \right)^2 \times 91.5 = 1.797 \times 10^{-3}\,\mathrm{m}^3 \tag{8}$$

and then the initial charge density, ρ_0, becomes

$$\rho_0 = \frac{Q}{V} = \frac{186.3 \times 10^{-9}}{1.797 \times 10^{-3}} = 103.7 \times 10^{-6}\,\mathrm{C/m^3}. \tag{9}$$

In Eq. (5), the variable of time, t, can be rewritten using the traveling distance and the average flow velocity , then,

$$\rho = \frac{\rho_0}{1 + \dfrac{d}{U\tau}}. \tag{10}$$

The values in Eq.(7) to (9) are put into the Eq. (10), ρ is calculated. In Fig. 9 the curves of the charge density calculated from experimental results and that of estimation from the hyperbolic law are compared. Where the mobility of positive and negative ions is used of $\mu_+ = 1.4\times10^{-4}\,\mathrm{m^2/V\cdot s}$, $\mu_- = 1.9\times10^{-4}\,\mathrm{m^2/V\cdot s}$, respectively [7]. The experimental values of the positive and negative ions are slightly smaller than the curves of the estimation from the hyperbolic law. From this difference between experimental results and the estimation from the hyperbolic law, the mobility of ions seems very important factor. Revising the value of the mobility to match the experimental results and the curves, the mobility of positive and negative ions will be $\mu_+ = 1.7\times10^{-4}\,\mathrm{m^2/V\cdot s}$, $\mu_- = 2.1\times10^{-4}\,\mathrm{m^2/V\cdot s}$, respectively. Then, the curves for the positive and negative ions show the good agreement with the experimental results. Our experiments have proceeded in an open room air. The most of value we could use find in the other's works is usually measured for dry ideal air. Some works suggested that the negative and positive ion mobilities becomes closer in moist gas [8], though the those value are still smaller than our empirical values.

The similar estimation has been done for the AC corona discharge. Figure 10 shows the relationships of the charge density of the ion cloud and the transferred distance. There is little effect on the frequency of the applied voltage. In order to compare the plots to the estimation from the hyperbolic law, the initial charge density ρ_0 at 1, 10 and 100 Hz in experiments are averaged to utilize as the initial charge density for estimation. The average flow velocity was set 91.5m/s and the mobility of positive and negative ions was set of $\mu_+ = 1.7\times10^{-4}\,\mathrm{m^2/V\cdot s}$, $\mu_- = 2.1\times10^{-4}\,\mathrm{m^2/V\cdot s}$, respectively, in the estimation.

The curve from the estimation shows a good agreement with the experimental results.

C. *Estimation of ion mobility from hyperbolic law*

As discussed in Section 4B, the experimental results and the estimation from hyperbolic law shows very good agreement in the relaxation characteristics of a transferred ion. The value of the ion mobility takes a very important place in hyperbolic law. In this section, the ions mobility will be estimated from hyperbolic law.

The initial charge density is written as the following equation,

$$\rho_0 = \frac{i_0}{AU}, \tag{11}$$

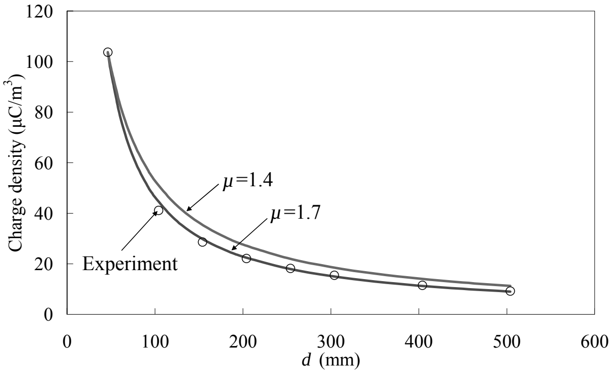
where i_0 is the ion current, U is the average flow velocity and A is the cross section of the pipe. The charge density at the traveling distance d is described as

$$\rho = \frac{i}{AU}. \tag{12}$$

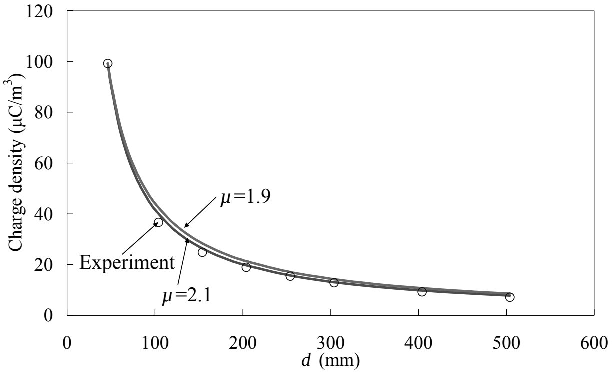
Substituting Eqs. (11) and (12) into Eq. (10), Equation (10) becomes

$$\frac{\mu}{\varepsilon AU^2} = \frac{i_0 - i}{i_0 i d}, \tag{13}$$

giving,

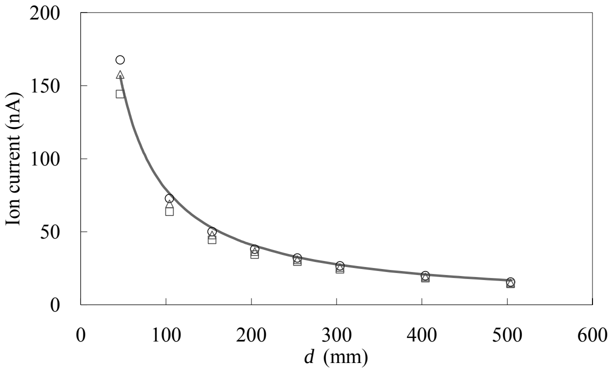


(a) Positive ion

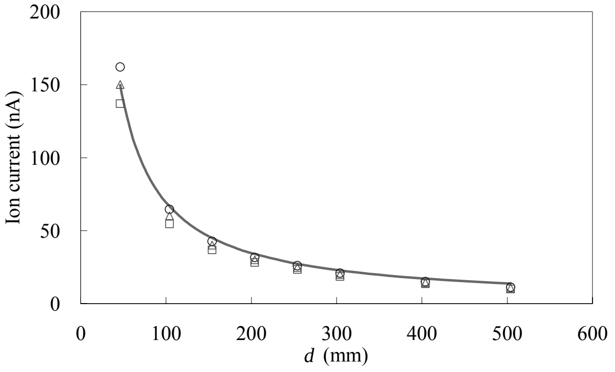


(b) Negative ion

Fig. 9. Comparison of experimental value of DC corona and the simulated curve.



(a) Positive ion



(b) Negative ion

Fig. 10. Comparison of experimental value of AC corona and the simulated curve.

$$\mu = \varepsilon A U^2 \frac{\frac{1}{i} - \frac{1}{i_0}}{d}. \quad (14)$$

Now, the ion mobility μ is estimated empirically from the ion current and the traveling distance. From a difference of traveling distance d_1 and d_2,

$$\mu = \varepsilon A U^2 \frac{\frac{1}{i_2} - \frac{1}{i_1}}{d_2 - d_1}. \quad (15)$$

The mobility of positive and negative ions lead from this equation was $\mu_+ = 1.74 \times 10^{-4}\,\mathrm{m^2/V \cdot s}$, $\mu_- = 2.26 \times 10^{-4}\,\mathrm{m^2/V \cdot s}$, respectively. Those values are very close to the calculation from the averaged values for a DC corona at 4.5kV (Cf. Section 4.B). Furthermore, this value is good agreement with the ions mobility given in some other work [8]. In Eq. (10), however, the estimated relaxation characteristics of transferred ion density are sensitive to the average flow velocity. In this report, we calculated the average flow velocity from the phase difference between the waveforms at two different transferred distances. Further discussion on the method to get more precise value of the average flow velocity should be needed.

V. CONCLUDING REMARKS

Connecting a Faraday cage directly to an AC ionizer, the transferred charge amount can be measured without any interference by means of the induction current. In addition, changing the pipe length between the ionizer and the Faraday cage, the relaxation characteristics of transferred ions through a pipe are well defined. The results are summarized as follows.

(1) The transferred charge amount is decreased with the traveling distance.
(2) For AC corona under frequency 100Hz, the transferred charge amount per 1 second is not varied in frequency.
(3) The dependency of the transferred charge amount on the pipe length shows very good agreement with the estimation via hyperbolic law.
(4) The estimation of a transferred charge amount by hyperbolic law is sensitive to the ion velocity and ion mobilities.

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