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Measurement of ac ion current from a corona ionizer using a Faraday cage

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Abstract

The use of ac ionizers operating at high frequency has become common in the semiconductor industry. The mechanism by which equipment neutralizes charge, however, is not well understood, because ac induction interferes with the measurement of extremely small ion currents. In this work, we use a Faraday cage that is directly connected to an ac ionizer. At frequencies of 1 and 10 Hz, we measure distinct pulses of ion current. The amount of transported charges increases with both applied voltage and ambient pressure. The effect of pressure is more significant than the effect of voltage. At the higher chosen frequency, the current changes from pulses to a sinusoidal shape. By noting the delay time at 1 kHz, the average air velocity between the needle and the Faraday cage was calculated. From dc corona measurements inside the ionizer outlet, we determine that the fraction of charge transported to the Faraday cage is small compared to the total amount of charge generated by corona.

Keywords: Corona; Ionizer; Faraday cage; AC corona; Charge neutralization

1. Introduction

The elimination of electrostatic charge is extremely important in the electronic industry, particularly those operations involved in producing semiconductor devices, disk drives, liquid-crystal displays, and other static-sensitive devices. One possible method for eliminating unwanted charge is to provide a conducting path from the work piece to ground. In most practical situations of interest, however, non-conductive materials predominate on production lines. Similarly, the work piece itself is often insulating. In such situations, ionized air is often used to provide the conducting path needed to remove charge from non-conducting materials, and also from ungrounded conducting objects.

Although there are many different charge elimination systems that produce air ions, including those that rely on corona discharge, radioactive isotopes, soft X-rays, and ultraviolet radiation, the most widely used in industry settings is the corona ionizer [1–3]. Within the category of corona ionizers, several different types may be found. Historically, the dc ionizer has been the most widely used. A dc ionizer uses two ion emitters driven by separate positive and negative high voltage supplies to produce ions of both polarities. Another approach to it is to use a single electrode driven by a high-voltage ac source. Such an ac-driven electrode produces positive and negative ions alternately over each ac cycle. Generally, an ac ionizer is driven at the power line frequency (e.g., 50 or 60 Hz), although some high-frequency ionizers can be found.

It is generally believed that when the polarity applied to a corona electrode is rapidly changed at high frequencies, the two polarities of charges generated do not separate sufficiently in space; therefore, the ions rapidly recombine. For this reason, ac ionizers tend to operate at low frequencies. Conversely, a number of researchers have found that an electrode energized with high-frequency voltage can eliminate unwanted surface charge effectively [4,5]. One advantage of a high-frequency system is that it can utilize a compact, piezoelectric power supply as the

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high-voltage source. For example, Koganei Corp. markets such a high-frequency, high-voltage ionizer combined with an air blower system.

Although it has become clear that a high-frequency, high-voltage ionizer is effective for charge elimination, the fundamental mechanism of the charge neutralization process is not well understood in the high-frequency regime. For this reason, we have begun to investigate the fundamental characteristics of high-frequency ac corona. Although our ultimate focus is on high-frequency ac corona, we found the measurement of such corona to be extremely difficult; hence we begin our experiments at lower frequencies than that found in high-frequency ionizers.

2. Experimental apparatus and procedure

The steady-state neutralization performance of an ionizer is customarily evaluated using a charged-plate monitor (CPM) system [6]. If the instantaneous ion current to the charged plate is monitored using an oscilloscope or high-speed electrometer, the measured signal is obscured by the induction current caused by the high-voltage electrode or ambient charge cloud. This induced ac current can be much larger than the ion current itself. To solve this problem, we have developed a ‘‘suction’’ type of Faraday cage. By placing the inlet of such a Faraday cage near the outlet nozzle of the ionizer, the ion current alone can be measured without being affected by induced currents. Such measurements may not be perfectly reproducible, however, because the precise positioning of the inlet tube can be difficult to determine. In our experiments, the Faraday cage is therefore connected directly to the ionizer output nozzle via a very short connecting pipe.

A schematic diagram of our experimental apparatus is shown in Fig. 1. It consists of a Koganei blower type ionizer, a Faraday cage, and the short connecting pipe. The ionizer itself contains sharp, needle electrodes. Pressurized air is sent to the nozzle, and the ions produced inside the nozzle are blown into the Faraday cage. The inner cylinder of the Faraday cage is connected to an oscilloscope or electrometer to measure ion current.

3. Results and discussion

3.1. Corona current at low frequency

When ac voltage is applied to the needle electrode, charges of alternating polarity are generated near the needle tip. When compressed air is introduced into the nozzle housing, as shown in Fig. 1, these ions are transported to the Faraday cage. An oscilloscope connected to the inner cylinder shows that measurement of the ion current was possible. The voltage reading of the oscilloscope can be converted into a current value by dividing the former by the oscilloscope input impedance, in this case equal to 1 MΩ.

Typical oscilloscope traces showing applied voltage and Faraday cage current are shown in Fig. 2. The data shown in Fig. 2 were collected with an 8 kV peak-to-peak voltage applied to the ionizer at an ambient air pressure of 0.2 MPa, and at frequencies of 1 Hz (Fig. 2a) and 10 Hz (Fig. 2b). The plots of Fig. 2 indicate that during the positive and negative half-cycles, positive and negative ions, respectively, are collected by the Faraday cage.

When the frequency of the applied sinusoidal voltage is 1 Hz, the corona currents at positive and negative polarities appear to have the same magnitude and time duration. Distinct threshold voltages for corona onset and corona cessation are evident. At 1 Hz, these thresholds have the same value. At 10 Hz, however, the onset voltage is larger than the cessation voltage.

As Figs. 2(a) and (b) reflect only typical examples of many possible sets of parameters, measurements were repeated by changing the various parameters. The results of these tests, averaged over three values, are summarized in Table 1.

In the case of 1 Hz, the average voltage measured by the oscilloscope connecting the Faraday cage to ground was 189 mV. The input impedance of the oscilloscope is 1 MΩ; hence this measured voltage value reflects a positive current of 189 nA. At 1 Hz, the average duration of the corona phase was 216 ms, or about 40% of the half-cycle. Multiplying the average duration by the average current yields a total charge transfer of 4.08 nC. Similar results were found at 1 Hz for the negative portion of the cycle.

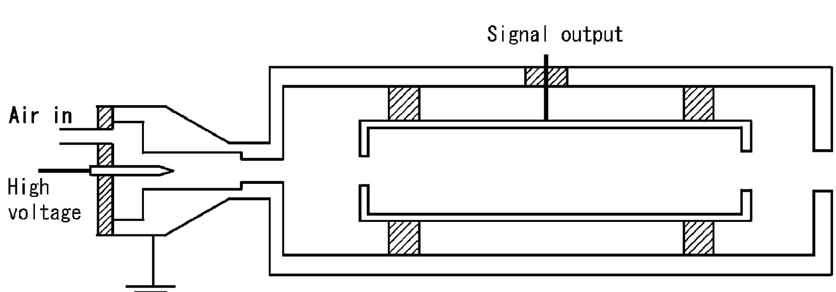

Fig. 1. Experimental apparatus.

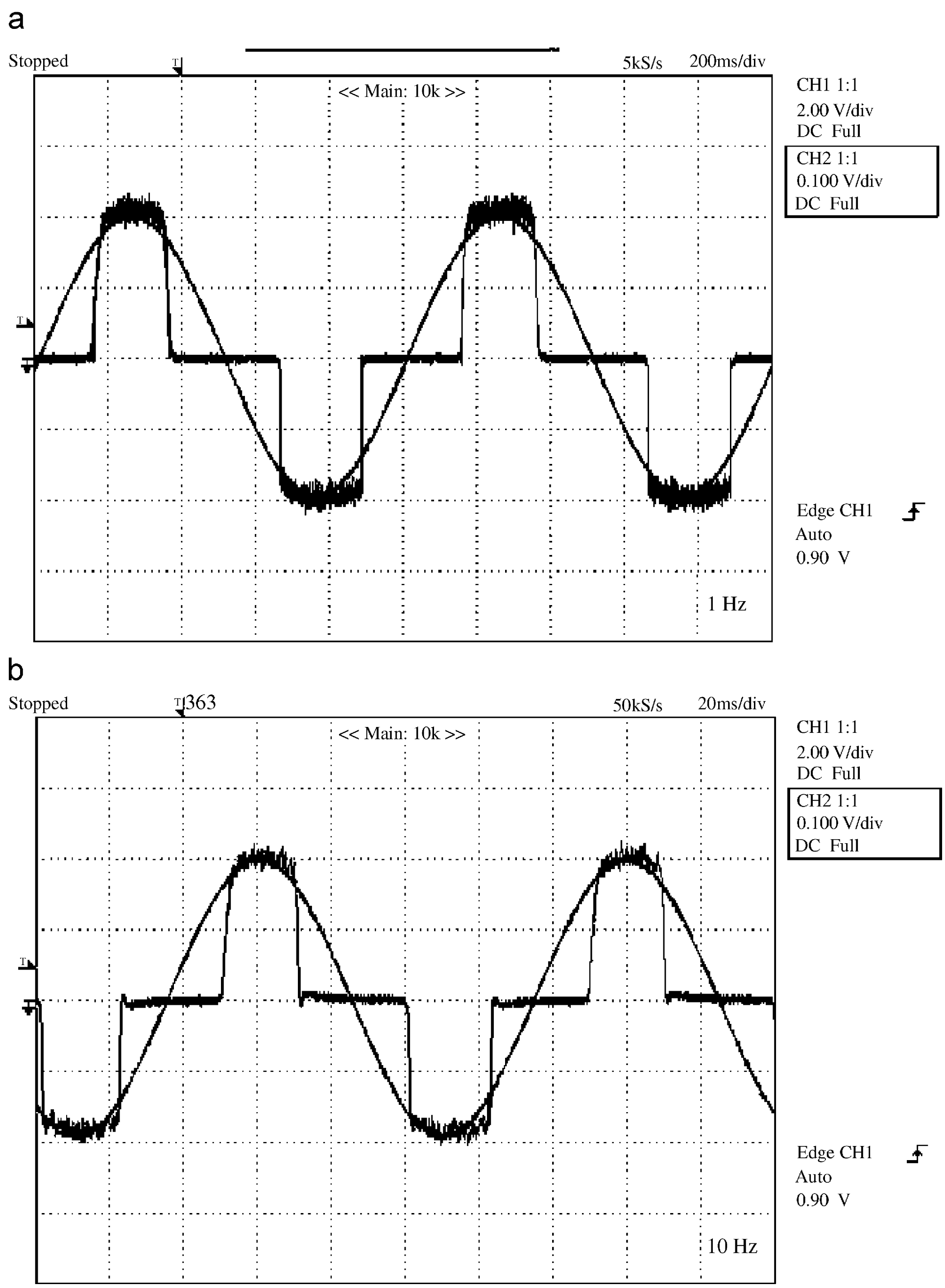

Fig. 2. Measured configuration of wave shape: (a) frequency of 1 Hz and (b) frequency of 10 Hz.

Table 1
Average values of Faraday cage measurement

Frequency (Hz)	Positive part			Negative part		
	Voltage (mV)	Time (ms)	Charge (C)	Voltage (mV)	Time (ms)	Charge (C)
1	189	216	4.08×10^{-8}	−189	230	-4.35×10^{-8}
10	176	21.6	3.8×10^{-9}	−172	24.1	-4.13×10^{-9}

Although in the case of 10 Hz, the discharge duration is only 10% of measured at 1 Hz, the total duration in 1 s is almost the same.

Similar measurements were performed for different values of voltage applied to the needle electrode, and also at different values of air pressure. Fig. 3 shows the

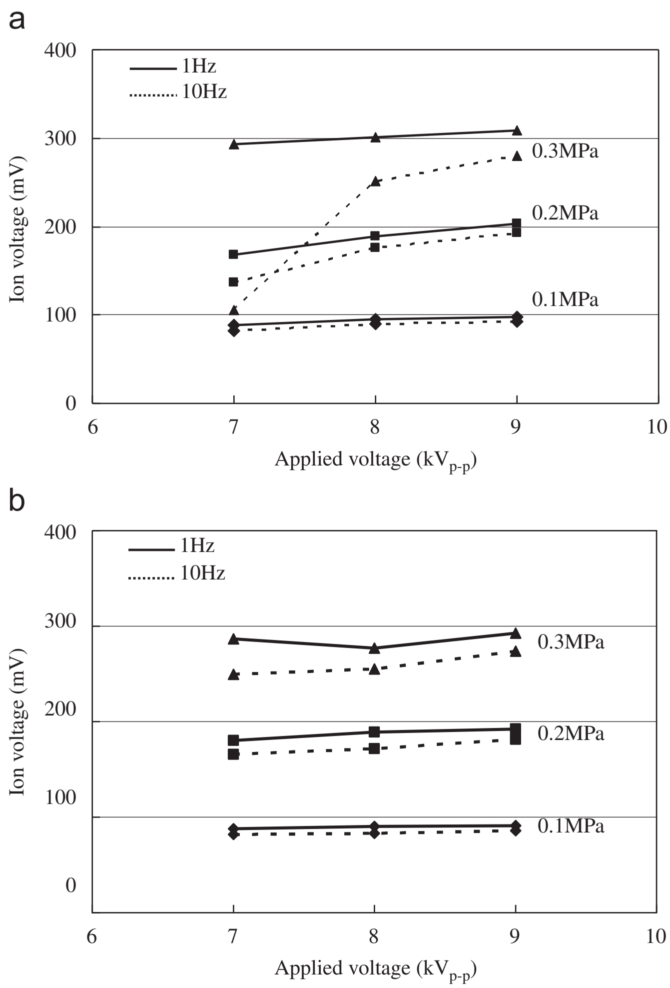

Fig. 3. Dependency of ion voltage on applied voltage. Dividing ion voltage by 1 MΩ transfers to ion current: (a) positive ion and (b) negative ion.

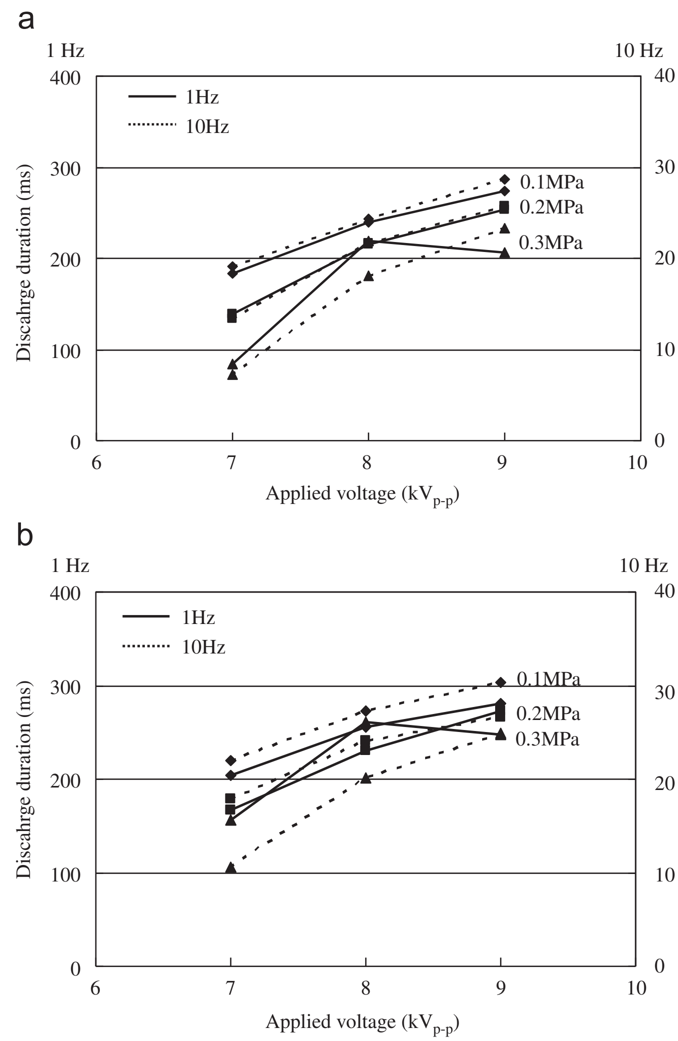

Fig. 4. Dependency of discharge duration on applied voltage: (a) positive ion and (b) negative ion.

dependency of the Faraday cage voltage on the peak value of the applied high voltage at different air pressures. (Note that increasing the air pressure into the ionizer nozzle increases the air flow velocity.) As one can see, for both positive and negative polarities, the dependence of ion current on voltage is, for the most part, not large, regardless of the pressure. One peculiarity exists at the data point 10 Hz and 0.3 MPa. At this higher pressure, the corona discharge becomes unstable or intermittent.

The dependency of discharge duration on applied voltage is quite significant, as shown in Fig. 4. Because the number of ions collected by the Faraday cage is proportional to the measured Faraday cage voltage and discharge duration, this figure suggests that the collected charge increases with applied voltage.

Figs. 5 and 6 show the dependency of collected ions on air pressure. When the pressure increases, the ion current increases. The one anomaly occurs for positive ions at 7 kV and 10 Hz. One of the reasons may be the higher air velocity which can transport more charge per unit time to the Faraday cage. As we will see later, this is not only the reason for the observed anomaly. In contrast to ion current, the duration of the discharge decreases with increasing air pressure, as shown in Fig. 6. In general, the collected charge increases with air pressure. However, at a voltage level of 7 kV, the number of positive ions does not increase with pressure, because the low voltage and high speed of the air flow cause the discharge to become unstable. (See, for example, the curve taken at 10 Hz and 0.3 MPa.) At this higher pressure, the corona discharge becomes quite unstable, and at times, it becomes intermittent.

3.2. Corona current with higher frequency

When the frequency of applied voltage is increased, the waveform shape and point-of-onset of the ion current change dramatically, as shown in Fig. 7, for frequencies of 100, 300, 500, and 1000 Hz. The differences can be clearly seen by comparing Fig. 7 to the lower-frequency plots of Fig. 2.

At 100 Hz, the ion current over the non-discharge interval is no longer flat, but instead has some slope. With

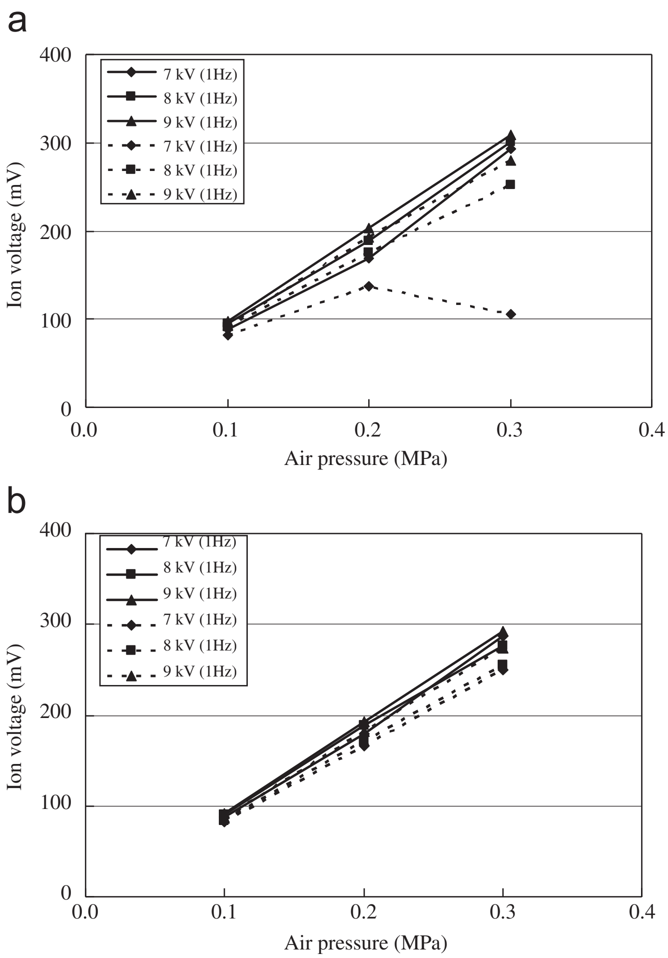

Fig. 5. Dependency of ion voltage on air pressure. Dividing ion voltage by 1 MΩ transfers to ion current: (a) positive ion and (b) negative ion.

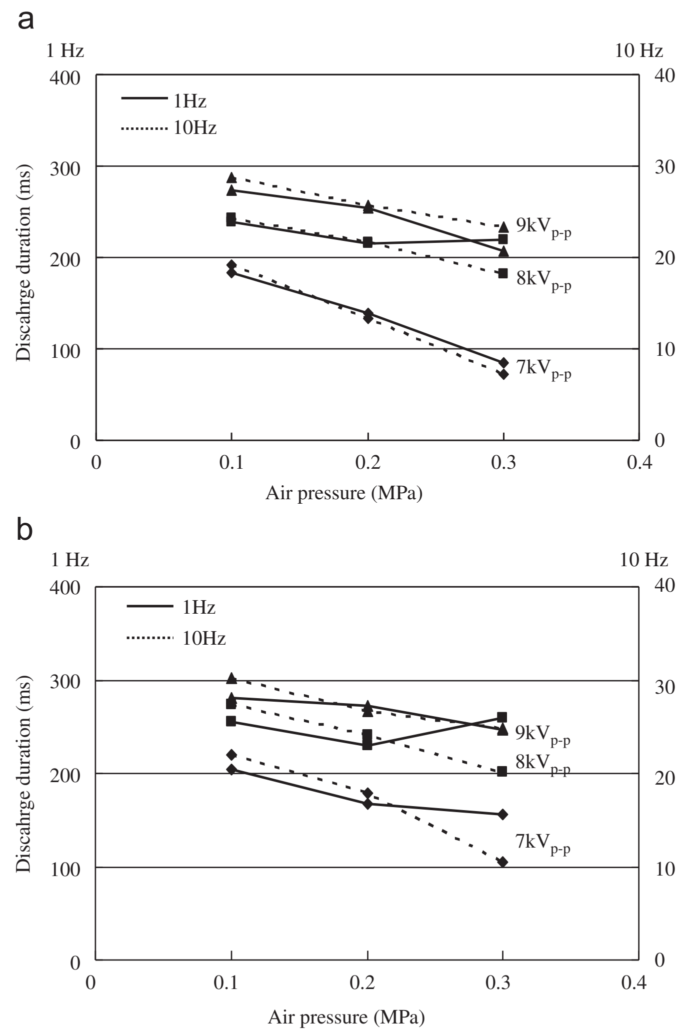

Fig. 6. Dependency of discharge duration on air pressure: (a) positive ion and (b) negative ion.

further increases in frequency, the shape of the ion current changes from a pulse mode to a waveform having a nearly sinusoidal shape. A more important attribute of the waveforms at high frequency is the delay of the current with respect to voltage.

At low frequency, the ion transfer time from the needle to the Faraday cage is negligibly small compared to the ionization duration. However, as the frequency becomes ever higher, the transfer delay becomes more significant.

At 1 kHz, and at various values of air-nozzle pressure, the delay time between the voltage and current waveforms was measured. The results are shown in Table 2. The distance from the tip of the needle electrode to the Faraday cage input port was 46.3 mm; hence the average air speed can be calculated. These results are also shown in Table 2. One can see the average air speed is quite high because the diameter of connecting pipe is quite narrow.

3.3. DC discharge at nozzle

As shown in Fig. 3, the dependence of ion current measured by the Faraday cage on applied voltage is rather small. This result can better be understood by considering the illustration of Fig. 8. The threshold voltage is almost the same regardless of the peak applied voltage; hence the discharge duration becomes longer at higher applied voltages. However, as already shown, this dependency is rather small.

To obtain the highest possible ion current, a dc voltage was applied to the needle electrode, with the charge emitted at the needle blown by the air stream into the cage. The results of this measurement are shown in Fig. 9, where dc as well as two ac cases is included. Except for the data point at 0.3 MPa and 7 kV, there is gradual increase in ion current with applied voltage. However, this trend is not significant. The three curves taken at an air pressure of 0.2 MPa show a clear dependency of ion current on frequency.

For the purpose of better understanding our data, we attempted to measure the corona current versus voltage characteristic of the ionizer nozzle itself. Because the ionizer needle is encapsulated inside the nozzle housing, the needle current must be measured on the high-voltage

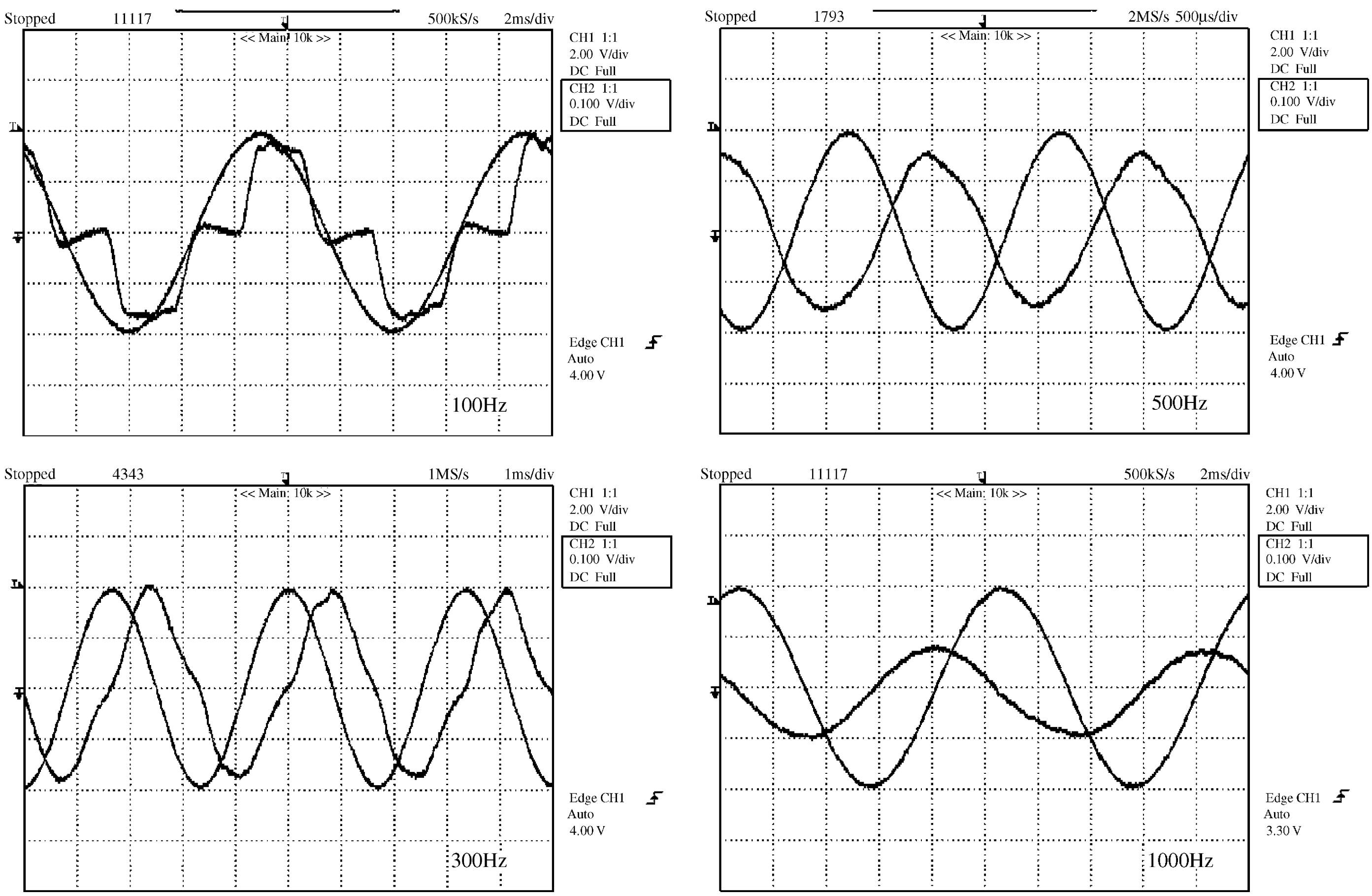

Fig. 7. Measured configuration of wave shape.

Table 2
Delay time and average velocity

Air pressure (MPa)	Flow rate (L/min)	Delay time (μs)	Average velocity (m/s)
0.1	79	946	48.9
0.2	127	747	62
0.3	172	663	69.8

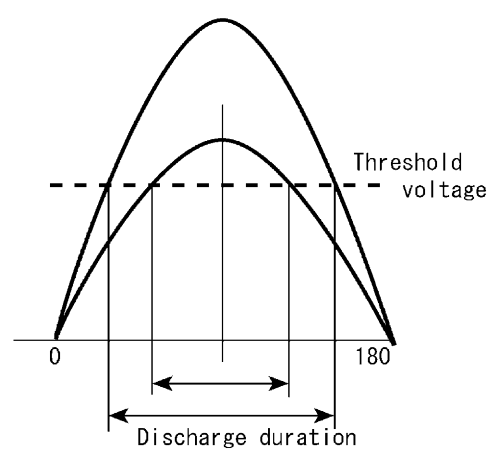

Fig. 8. Schematic illustration of discharge duration with different voltage.

side using a floating ammeter, as shown in Fig. 10. For this purpose, we calibrated a simple hand-held, battery-operated multi-meter using a precision electrometer. The hand-held multi-meter thus served as a usable piece of equipment for this purpose.

Plots of needle emitter current versus applied dc voltage at various pressures are shown in Fig. 11. As is known in the field, negative corona current is generally larger than positive corona well above corona onset.

Plots of the ion current transported to the Faraday cage are shown in Figs. 12(a) and (b). Even when the corona current to the nozzle is very different at negative and positive polarities, the charge transferred to the cage is almost the same. The highest ion current to the Faraday cage is 0.3 μA, occurring at 0.3 MPa and negative polarity. Conversely, the maximum current from the needle under the same conditions is 25 μA. Hence only 1% of the charge emitted by the needle is transferred to the cage. The positive case is somewhat different. Because the needle current is much smaller than in the negative polarity case, the ion transfer ratio at 0.3 MPa and 4.5 kV is about 5%.

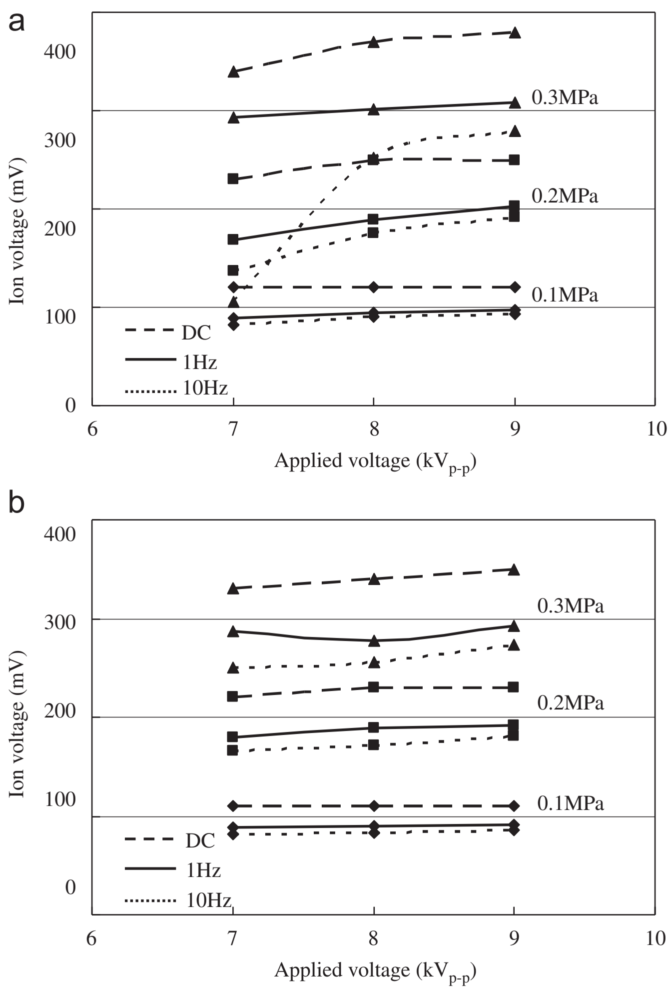

Fig. 9. Dependency of ion voltage on applied voltage. Dividing ion voltage by 1 MΩ transfers to ion current: (a) positive ion and (b) negative ion.

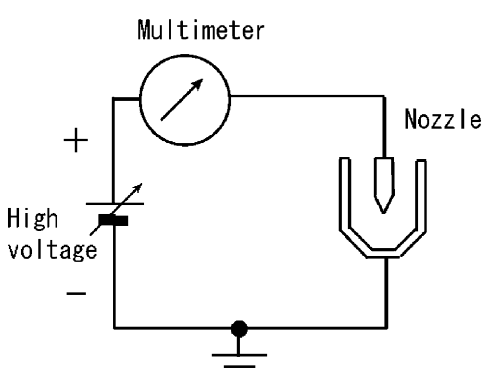

Fig. 10. Ion current measurement with floated state.

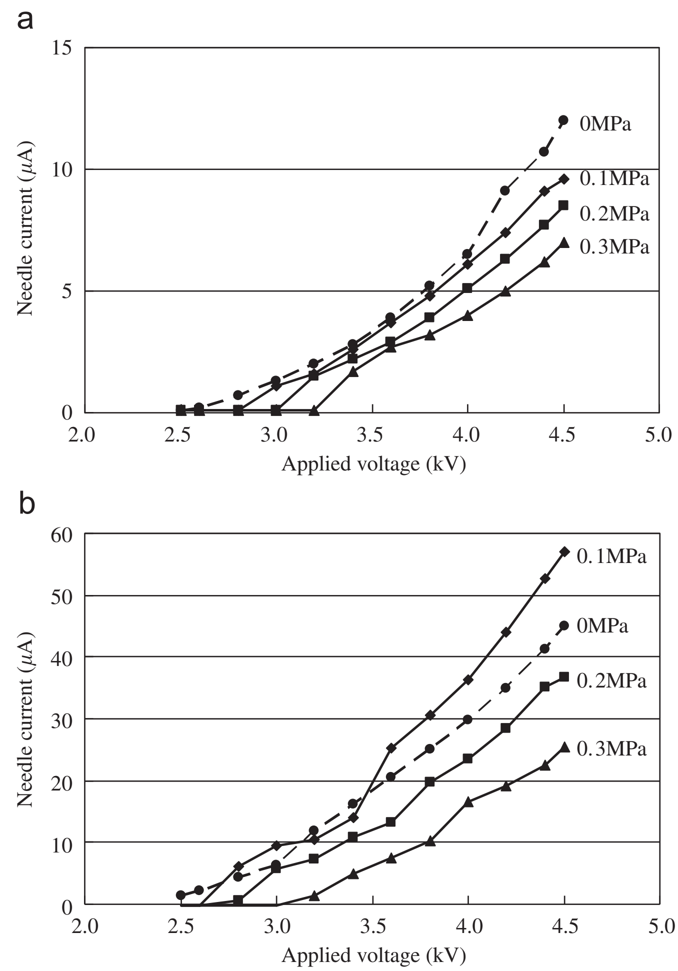

Fig. 11. Dependency of needle current on applied voltage: (a) positive ion and (b) negative ion.

An interesting phenomenon was observed when the negative voltage was applied to the needle and an air stream added. As shown in Fig. 11(b), the needle current at zero pressure is not the highest, and some air flow enhances the nozzle current. In this figure, the current becomes highest at 0.1 MPa. However, there seems to exist a maximum current at a pressure value somewhere between 0 and 0.2 MPa. Because this enhancement could be caused either by pressure or air velocity; further experimentation was performed by closing the outlet of the nozzle housing that stops the air flow, but with pressure added. For the case of no air flow and higher pressure, the ion current was reduced. One can therefore conclude that the enhancement of current is due to air flow near the nozzle. An exact interpretation of this phenomenon will require knowledge of the precise air flow pattern in the nozzle.

4. Concluding remarks

By connecting a Faraday cage directly to an ac ionizer nozzle, transported charges were measured without any interference due to induction current. The results are summarized as follows.

(1) At frequencies of 1 and 10 Hz, the measured ion current took the form of square pulses with respect to time. At these frequencies, the transported charge increased with applied voltage and pressure. The effect of pressure was more significant than that of voltage.

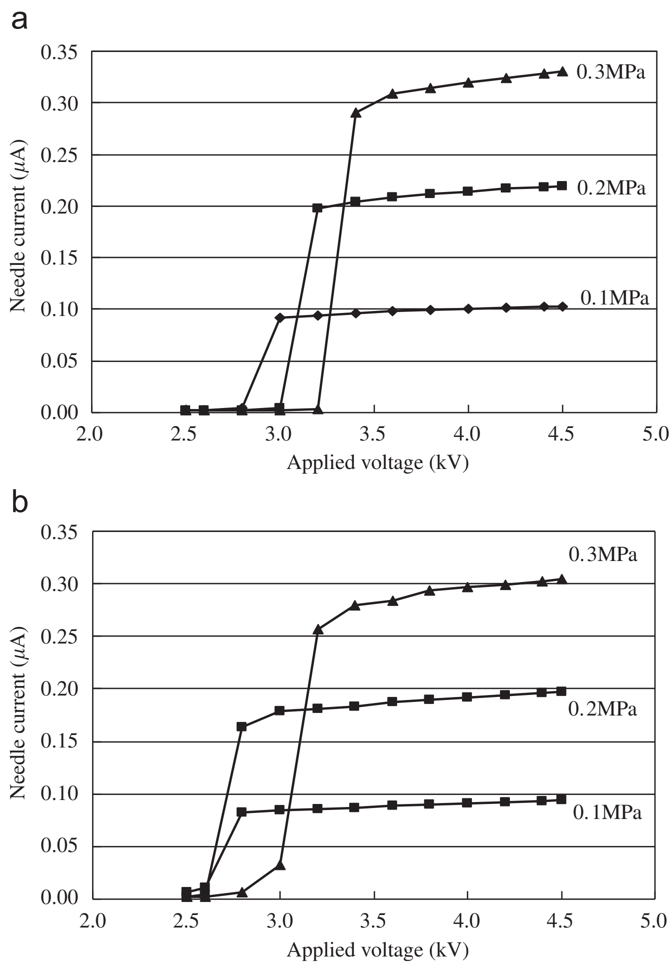

Fig. 12. Dependency of transmitted ion current on applied voltage: (a) positive ion and (b) negative ion.

(2) At higher frequencies up to 1 kHz, the current waveform changed from a pulse to a sinusoidal shape. The time delay of the measured signal with respect to the applied voltage became more significant. From the measured delay time at 1 kHz excitation, the average air velocity between needle and Faraday cage was calculated.

(3) DC corona current measurements inside the ionizer showed that negative corona current is much larger than positive well above corona threshold. The portion of transported charge from the nozzle to the Faraday cage is 5% or less, and little polarity effect is observed.

Acknowledgment

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