PHYSICS OF PLASMAS 21, 043511 (2014)

Relation between plasma plume density and gas flow velocity in atmospheric pressure plasma

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(Received 10 March 2014; accepted 15 April 2014; published online 24 April 2014)

We have studied atmospheric pressure plasma generated using a quartz tube, helium gas, and copper foil electrode by applying RF high voltage. The atmospheric pressure plasma in the form of a bullet is released as a plume into the atmosphere. To study the properties of the plasma plume, the plasma plume current is estimated from the difference in currents on the circuit, and the drift velocity is measured using a photodetector. The relation of the plasma plume density n_{plu}, which is estimated from the current and the drift velocity, and the gas flow velocity v_{gas} is examined. It is found that the dependence of the density on the gas flow velocity has relations of $n_{plu} \propto \log(v_{gas})$. However, the plasma plume density in the laminar flow is higher than that in the turbulent flow. Consequently, in the laminar flow, the density increases with increasing the gas flow velocity. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4873384]

I. INTRODUCTION

Recently, plasma techniques under atmospheric pressure have been adopted for industrial, biological, and medical applications.[1,2] Atmospheric pressure plasma of dielectric barrier discharge (DBD) is intermittently generated using a dielectric, rare gas, and metal electrode by applying RF high voltage.[3,4] A quartz tube is used as a dielectric, and plasma is released into the atmosphere. Plasma irradiation is applied for material processing without thermal damage under atmospheric pressure.[5,6] The properties of atmospheric pressure plasma, which generates plasma in open space rather than in a confined discharge gap, have recently been a topic of great interest and have been reported and reviewed.[7,8] A plasma plume is a small bullet-like volume of plasma traveling at unusually high velocities,[9–13] but the drift velocity of ions was estimated as almost zero.[14] The plasma temperature was kept near room temperature.[14,15] The properties of the highly localized so-called "plasma bullets" resemble the properties of cathode-directed streamers in positive corona discharges.[9,16] It is considered that the atmospheric pressure plasma of DBD is a thermally non-equilibrium state and the ion temperature is almost zero or much lower than the electron temperature. The plasma density is an important factor to examine the mechanism of plasma generation in such atmospheric pressure plasmas. On the other hand, in the development of industrial, biological, and medical applications, it is necessary to express the values of the plasma current and plasma density for an effective plasma supplement for a human body or materials. The effect of the plasma occurs by the generation of radicals such as ozone. The generation of ozone is investigated by an alternating current corona discharge.[17] The plasma current is estimated from the difference in currents with and without plasma on the circuit.[9,15,18] The current of the plasma plume is related to the density and the drift velocity of the plasma plume. The density of the plasma plume has been estimated as $\sim 10^{18}\,\mathrm{m}^{-3}$ from measurements.[18] In addition, the release of the plasma plume into the atmosphere is influenced by the state of gas flow.[19] The behavior of plasma plume (bullets) is related to the hydrodynamic instability of the gas flow.[20] The state of gas flow is defined by gas flow velocity and cross-section of flow channel. The gas flow velocity is related with dynamic pressure, and the pressure is related with density. It is necessary to examine experimentally the relation between the plasma plume density and the state of gas flow.

In this study, we will describe the experimental results on atmospheric pressure plasma using a quartz tube and copper foil electrodes by applying RF high voltage. We study experimentally the properties of the plasma plume current and density. The relation between the plasma plume density and gas flow velocity is examined with various tube inner diameters.

II. EXPERIMENTAL SETUP

A. Experiment configuration

Figure 1 shows a schematic diagram of the atmospheric pressure discharge system using a quartz tube and copper electrodes, and measurement systems. The dielectric tube is made of quartz, its inner diameters are about 1.5, 2.5, 3.5,

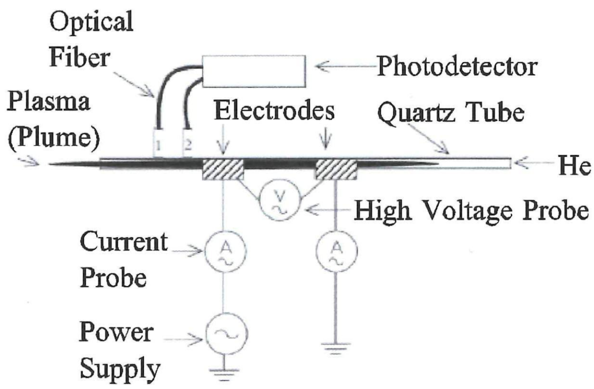

FIG. 1. Schematic drawing of atmospheric pressure plasma device and measurement systems.

4.5, and 7.7 mm, and its thickness is about 1 mm. The powered and grounded electrodes are made of a copper foil of 20×20 mm and a thickness of 0.1 mm. The distance between the electrodes is 40 mm. The distance between the powered electrode and the quartz tube edge is 50 mm. The helium gas flows in the direction of the powered electrode from the grounded electrode. The helium gas flow is controlled by a gas mass flow controller. The AC power supply (LHV-13A, Logy Electric) has a voltage from −6 to +9 kV and a main frequency of about 13 kHz, and the usual waveform is an asymmetric sine-wave about the ground line.

B. Measurement systems

The applied high voltage is measured by the high voltage probe (P6015A, Tektronix). The power and ground line currents are measured by the current monitor (model 4100, Pearson Electronics) on the power and ground lines, and the former is referred to as I_{pow} and the latter as I_{GND}.

The drift velocity of plasma plume is measured indirectly by the drift velocity of the luminous bullet by the time of flight method.[18] The emission of plasma lights is measured using the photodetector (PD) through an optical fiber. The measurement points are set to 5 (PD2) and 15 (PD1) mm from the edge of the powered electrode, and the measurement distance is 10 mm. The signals are digitized with a digital oscilloscope.

III. EXPERIMENTAL RESULTS

A. Plasma plume current and drift velocity

The plasma plumes are generated in two places of the left side of the left (powered) electrode and the right side of the right (grounded) electrode. The current of plasma plume on the upstream side of the quartz tube is eventually almost collected to the grounded electrode. The plasma plume on the downstream side is released into the atmosphere, and its current is a loss current from the circuit to the atmosphere. Therefore, the plasma plume current I_{plu} into the atmosphere is estimated using the subtraction of I_{GND} from I_{pow}.[18] The time evolutions of applied voltage, currents, and PD2 signal in the case of 2.0 slm of helium gas flow rate and inner diameter of 1.5 mm are shown in Fig. 2. In the figure, each curve is obtained from the moving average (100 ns time duration). A small amount of I_{plu} and the signal of PD2 are generated from the beginning of discharge with a very low voltage and I_{plu} continues up to about 6 μs. The PD2 signal is confirmed only in the positive phase. The plasma plume current in each inner diameter shows a similar waveform. The time averages of I_{plu} as a function of the gas flow rate in each inner diameter are shown in Fig. 3. The error bars shown in all figures denote the maximum and minimum values over multiple discharges, and the curve is a cubic spline. The time averages of I_{plu} in each inner diameter are almost independent of the gas flow rate, and the values of I_{plu} are between 3 and 7 mA. The plasma generation condition is related to the product of the inner diameter and gas pressure,[21] but the release of plasma into the atmosphere is not related to the inner diameter.

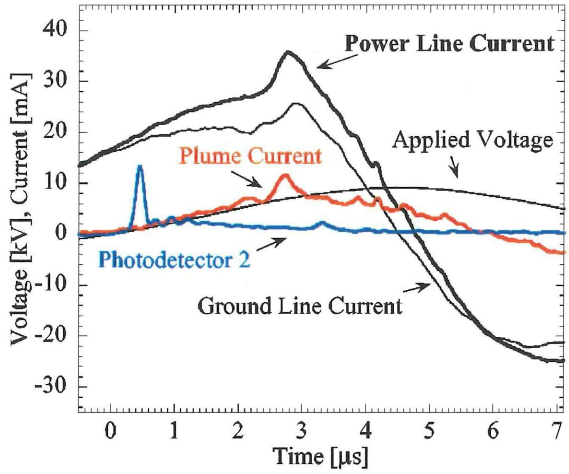

FIG. 2. Time evolutions of applied voltage, currents, and photodetector signal at 2.0 slm.

The plasma bullet travels with the emission of light, which is caused by helium plasma. The drift velocity of plasma plume is measured indirectly by the drift velocity of the luminous bullet by the time of flight method.[18] The traveling of the luminous bullet with the plasma light emission is coincident with the behavior of a positive streamer caused by photoionization.[9,13,22] In the photoionization theory, a high-speed ionization front is present, traveling at a velocity qualitatively equivalent to the electron drift velocity.[22] The dependences of drift velocity on the gas flow rate in each inner diameter are shown in Fig. 4. The values of drift velocity in each inner diameter are between 5 and 20 km/s. In each inner diameter, it is found that the drift velocity in the low gas flow rate for the most part is slower than that in the high gas flow rate.

B. Plasma plume density

The plasma is generated over the inside quartz tube, and its shape is a ring[23] and travels with a donut (ring) shape.[24]

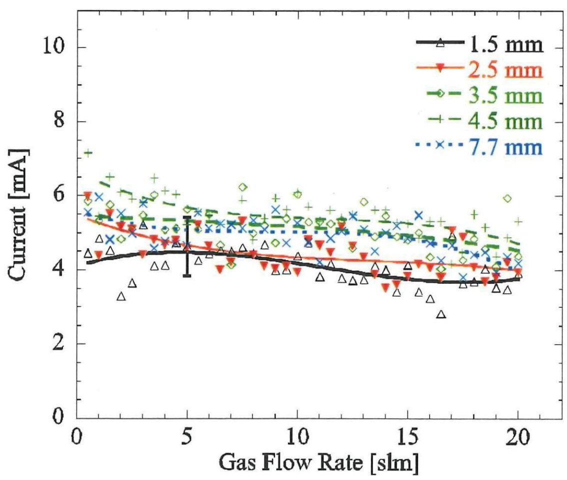

FIG. 3. Dependences of time average of plasma plume current on gas flow rate.

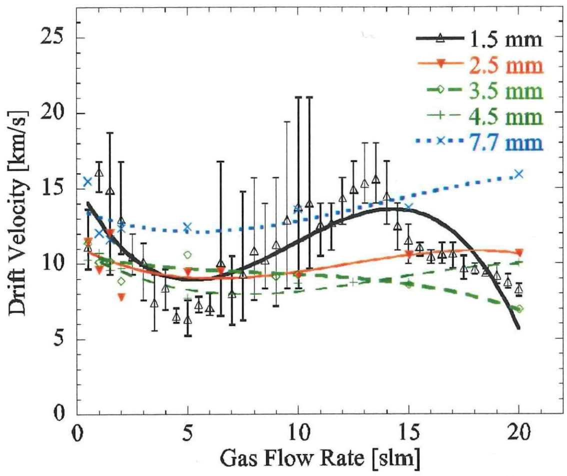

FIG. 4. Dependences of drift velocity of plasma plume on gas flow rate.

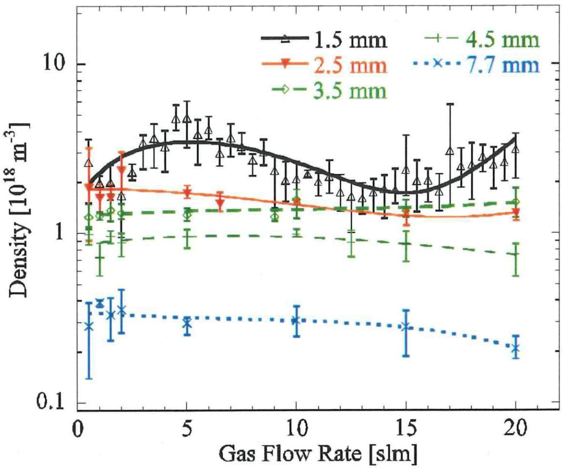

FIG. 5. Dependences of plasma plume density on gas flow rate.

The effect of plasma irradiation is generated with a ring shape on an object surface. Thus, the current of plasma plume is mainly retained with the ring shape. The thickness of the plasma ring is about 0.3–0.4 mm in each inner diameter. In addition, the plasma thickness is independent of the inner diameter and the gas flow rate near atmospheric pressure. Thus, the thickness of the plasma ring is estimated as about 0.35 mm. The cross-section of plasma plume is estimated from the relations of the thickness and the outer diameter of plasma plume. For each inner diameter, the cross-sections of plasma plume are shown in Table I. The cross-section of plasma plume is linearly proportional to the tube inner diameter. The plasma plume density n_{plu} is estimated from the time average of the plasma plume current $\langle I_{plu}\rangle$, the drift velocity v_{dri}, and the cross-section of plasma plume S_{plu}, as follows:

$$n_{plu} = \frac{\langle I_{plu}\rangle}{e v_{dri} S_{plu}}, \quad (1)$$

where e is the elementary electric charge.[18] The plasma plume densities released into the atmosphere are plotted as a function of the gas flow rate in each inner diameter, as shown in Fig. 5. In the figure, the error bars are mainly affected by the plasma plume current. The plasma plume density in inner diameter of 1.5 mm is higher than that of 7.7 mm. The profile of the plasma plume density depends on that of the drift velocity mainly. The plasma density in the region of high gas flow rate is low compared with that in the low gas flow rate region in each inner diameter.

TABLE I. Cross-section of plasma plume in each tube inner diameter.

Tube inner diameter (mm)	Plasma cross-section (mm^2)
1.5	0.95 (0.9–1.0)
2.5	1.8 (1.7–1.9)
3.5	2.6 (2.4–2.7)
4.5	4.4 (4.2–4.6)
7.7	7.9 (7.4–8.4)

IV. DISCUSSION

The property of the plasma plume current depends on neither the gas flow rate nor the tube inner diameter. The release volume of plasma plume is not influenced by the experimental configuration. On the other hand, the drift velocity in the low gas flow rate tends to be faster than that in the high gas flow rate. Here, the helium gas flowing out of the quartz tube mixes with air in the atmosphere. The flow channel is composed of helium gas and air regions. Because a helium gas and the air do not react, the dynamic viscosity and the density of the fluid are calculated at a molar fraction of each gas to estimate Reynolds number Re on the flow channel. The diameter of the flow channel is the inner diameter of quartz tube. The blue portion like a sheath is the outside of plasma plume.[18,19] The helium plasma plume activates nitrogen near the blue portion of plume. The blue portion of plume is considered to be the boundary of helium gas and air. The mixture ratio of helium gas and air is estimated from the areas of the inside and the outside of boundary on the cross-section in the experimental observation. For each tube inner diameter, the mixture ratios of helium gas and air on the cross-section of the flow channel and the relations between the gas flow rate and tube inner diameter are shown in Table II. Only in inner diameter of 1.5 mm, the ratio of helium gas is higher than air. For different gas flow rate and different inner diameter, the background gas of the plasma could be different. Although the intensity of the emission

TABLE II. Mixture ratios of helium gas and air in each tube inner diameter and relations between gas flow rate and tube inner diameter.

Tube inner diameter (mm)	He: Air	Upper limit of laminar flow (Re ∼ 2300) (slm)	Lower limit of turbulent flow (Re ∼ 4000) (slm)
1.5	1: 0.6	6.0	10.0
2.5	1: 1.4	6.5	11.5
3.5	1: 1.5	9.0	15.5
4.5	1: 1.3	12.5	21.5
7.7	1: 1.0	22.5	40.0

from the plasma plume changes by the conditions, the main spectral lines hardly change. Thus, the main ions would not be different by the conditions. In addition, the plasma plume tapers and the mixture ratio is varied around the tip of plasma plume.[19] The mixture ratio of helium gas and air is 0:1 (case 01) on the boundary layer of helium gas and air. The upper and lower limits of laminar and turbulent flows in the case 01 are shown in Table III. The upper limit of laminar flow is lower than a case to include helium gas. The lower limit of turbulent flow in the case 01 is almost the same as the upper limit of laminar flow to include helium gas. The boundary of helium gas and air would be a boundary layer of the laminar and turbulent flows. In inner diameter of 1.5 mm, the drift velocity in the laminar flow tends to be slower than that in the turbulent flow. In turbulent flow, the propagation of the plasma plume (bullet) is more complicated.[19,20] Thus, the drift velocity of plasma plume is affected by the state of gas flow. The state of gas flow is defined from the gas flow velocity and the tube inner diameter. The gas flow velocity is calculated from the gas flow rate and the cross-section of quartz tube. The gas flow velocity at 10 slm and inner diameter of 1.5 mm are calculated as about 95 m/s, and this velocity is approximately three orders of magnitude slower than the drift velocity. In addition, the cross-section of plasma plume is linearly proportional to the tube inner diameter. Consequently, the plasma plume density depends on the drift velocity. In order to investigate the dependence of the plasma plume density on the gas flow velocity, the relation between the plasma plume density and the gas flow velocity in each tube inner diameter is shown in Fig. 6. It is found that the plasma plume density in fast gas flow velocity tends to be higher than that in slow gas flow velocity. The gas flow rate in each tube inner diameter is separated into the laminar and turbulent flow regions. The regional averages of plasma plume density in the laminar and turbulent flow regions with the gas flow rate in the case 01 are calculated, and the relations between the regional average of plasma plume density and gas flow velocity are shown in Fig. 7. In the figure, the average of gas flow velocity in the laminar flow is calculated from 0.5 slm to the gas flow rate of the upper limit of laminar flow in the case 01, and the average of gas flow velocity in the turbulent flow is other than it and each line is a logarithmic curve fit. The average density in the laminar flow region is higher than that in the turbulent flow region of the same gas flow velocity, because the drift velocity in the laminar flow tends to be slower than that

TABLE III. Relations between gas flow rate and tube inner diameter in case of He: Air = 0:1.

Tube inner diameter (mm)	Upper limit of laminar flow (case 01, Re ~ 2300) (slm)	Lower limit of turbulent flow (case 01, Re ~ 4000) (slm)
1.5	2.5	4.5
2.5	4.0	7.0
3.5	6.0	10.0
4.5	7.5	13.0
7.7	13.0	22.0

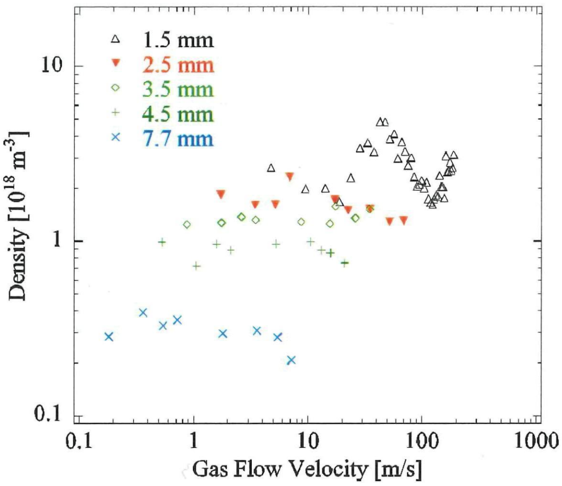

FIG. 6. Relations between plasma plume density and gas flow velocity.

in the turbulent flow. In addition, it is found that the dependence of the plasma plume density on the gas flow velocity v_{gas} has the following relation:

$$n_{plu} = f(x)\log(v_{gas}) + k, \quad (2)$$

where $f(x)$ is the function and k is the coefficient. The first term of the right-hand side is related to dynamic pressure. Thus, the increase of density is brought by increasing the dynamic pressure. However, the plasma plume density in the laminar flow is higher than that in the turbulent flow. An energy loss with the collision between helium and air in the turbulent flow is large compared with the case of the laminar flow. Thus, in the turbulent flow, a frictional force is strong compared with the case in the laminar flow. In addition, the plasma plume is released with electric charge into the atmosphere. An energy loss from electric charge to frictional force would cause a decline of the plasma plume density.

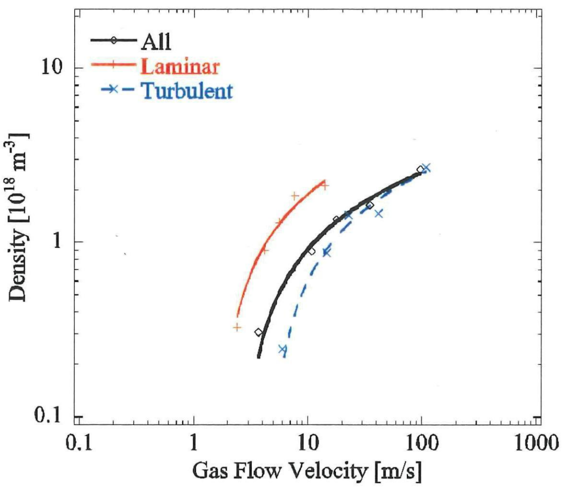

FIG. 7. Relations between regional average of plasma plume density and gas flow velocity.

V. CONCLUSION

We studied experimentally the properties of the plasma plume in the atmospheric pressure condition. The current of the plasma plume depends on neither the gas flow rate nor the tube inner diameter. The drift velocity of the plasma plume in the low gas flow rate tends to be slower than that in the high gas flow rate and is affected by the state of gas flow. Consequently, the plasma plume density depends on the drift velocity. On the other hand, the plasma plume density is related with the gas flow velocity logarithmically. The plasma plume density in fast gas flow velocity tends to be higher than that in slow gas flow velocity. Because an energy loss with the collision between helium and air in the turbulent flow is large compared with the case of the laminar flow, the plasma plume density in the laminar flow is higher than that in the turbulent flow.

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