Fundamental Characteristics of a New Type Plasma Generator[†]

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Abstract

Plasma jet at atmospheric pressure has the advantage of cost, because there is no need to prepare for costly chambers and vacuum pumps, and there are great possibilities in terms of its properties, high current density and high temperature. However, in general, most plasma jet generators consume large amounts of electric power, and it is difficult to realize a wide field application. Therefore, in order to resolve the problem, a new type plasma jet generator was developed, which is called a confront electrode type plasma jet generator from its configuration. In this study, the fundamental characteristics of the confront electrode type plasma jet generator have been investigated. The current range was from 15 to 25A for the working gas of argon. The electrical properties of the confront electrode type plasma jet generator were similar to those of the ordinary plasma jet generator. The temperature of the plasma jet near the Cu anode was about 8,000K from spectroscopy measurements.

KEY WORDS: (Confront Electrode Type), (Plasma Jet), (Electric Properties), (Plasma Temperature), (Emission Spectroscopy)

1. Introduction

Plasma jet technologies have been widely applied to plasma spraying, surface modification, and gases treatment. Particularly, for surface modification and gases treatment, low-pressure plasma processing is mainly used because of the stability of the discharge. However, a vacuum chamber is necessary for low-pressure plasma processing, and this involves high costs. On the other hand, in the case of atmospheric-pressure plasma processing, there is no need to prepare costly vacuum chambers. Realization of a stable discharge at atmospheric-pressure will contribute various industries economically. Presently, enough electric power is achieved when we use the atmospheric-pressure plasma generator as a heat source for thermal processing such as welding, cutting, spraying, etc.

The author developed a high power plasma jet, which was called gas tunnel type plasma jet, and the performances were clarified in previous studies [1-3]. For example, the gas tunnel type plasma jet, which is 200kW class, has high temperature of more than 20,000K and high energy density, also it has high thermal density of 80%. It is superior to the properties of other conventional type plasma jets [4]. Therefore this plasma has great possibilities for various applications to thermal processing [5]. As to the formation of high performance materials, high quality ceramic coatings were obtained by

the gas tunnel type plasma spraying method [6,7]; for example, typical alumina coating produced with Vickers hardness of Hv=1200-1600 [8]. As another application, the gas tunnel type plasma jet was applied to the surface nitridation of titanium. This experiment also investigated the possibility of the speedy formation of a high functional thick TiN coating [9,10].

In general, an atmospheric-pressure plasma jet generator consumes large amounts of electric power, and this limits its application field. Such high energy is not always necessary for use in applications like surface modification, gas treatment or other purposes. For this reason, the confront electrode type plasma generator has been developed as a small, high efficient type plasma heat source. This plasma generator can generate a stable discharge under atmospheric-pressure, and can be operated with about 1kW electric power.

In this paper, the fundamental characteristics of the confront electrode type plasma generator are investigated. Argon gas was used for the working gas and the current—voltage characteristics were measured at various conditions. The temperature of the plasma jet was measured by using spectroscopy.

2. Experimentals

2.1 Confront Electrode Type Plasma Generator

Figure 1 shows a schematic of the confront

electrode type plasma generator.   Plate material is used as each electrode, and the anode is made from copper, the cathode is made from tungsten.   The thickness of anode and cathode are 10mm, 5mm respectively.   This plasma generator has two inlets for gas, the one is located near the anode (main inlet) and the other is located near the cathode (sub inlet).   The gas from main inlet flows to the anode side, and that from sub inlet flows to the gap between anode and cathode.   The shape of plasma jet generated by a general plasma jet generator is a cone, but in the case of the confront electrode type plasma generator, the shape is a sheet.   And this generator has no nozzle.

Table 1 shows experimental conditions in this study. The DC power supply used has a range of 25A (maximum 3kW).   The working gas is Ar.   **Figure 2** shows the appearance of plasma jet taken by CCD video camera.
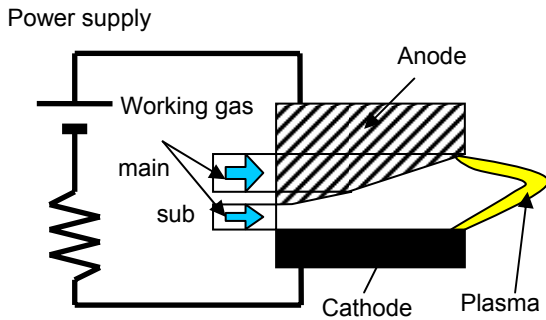

Fig.1 Schematic of confront electrode type plasma generator.

Table 1 Experimental conditions.

Power supply:	P=3kW (maximum)
	I=25A (maximum)
Working gas:	Ar
Gas flow rate:	Q_{main}=4-10 l/min
	Q_{sub}=4-10 l/min
Pressure:	p = 0.1MPa
Ignition:	High frequency discharging

2.2 Experimental Procedure

In this study the flowing subjects were experimentally investigated.
1)   The electrical properties of the confront electrode type plasma generator.
2)   The relation between discharge voltage and working gas flow rate.
3)   The temperature of the plasma jet.

2.2.1 Measurement of electric characteristics

During discharging, current and gas flow rate from main inlet and sub inlet can be changed.   Discharge current was changed from 24A decreasingly.   The plasma jet disappeared when the conditions were beyond the limit of discharge.   In the case of changing the gas flow rate, the discharge voltage was measured with fixed sub gas flow rate, while the main gas flow rate was changed increasingly.   The electric characteristics, mainly discharge voltages, were investigated under various conditions.   In addition, the dependence of the plasma jet width on discharge current was investigated from the picture of the plasma jet taken by CCD camera. From the picture, the distribution of the radiant intensity from plasma jet was investigated.   We regarded FWHM (Full Width at Half Maximum) of the radiant intensity as the width of the plasma jet, in this study.

2.2.2 Measurement of plasma temperature by using spectroscopic

Figure 3 shows a schematic of the measurement system.   Emission from the plasma jet was collected and transmitted to a monochromator (Nikon P-250 Monochromator) through lens and optical fiber. Scanning wavelength range was from 413nm to 430 nm. Boltzmann plots were made from each relative intensity
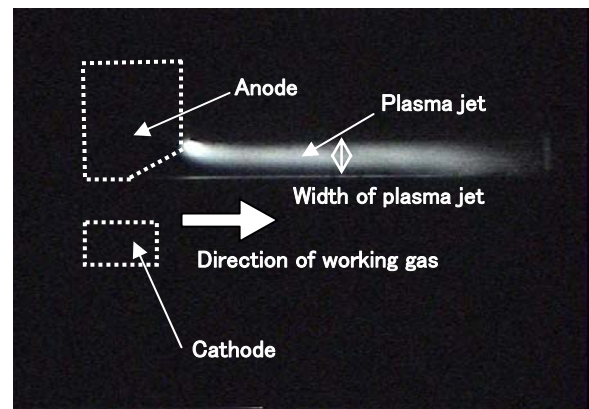

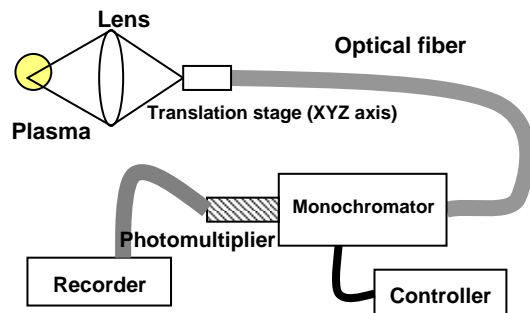**Fig.2** Appearance of plasma jet taken by CCD camera.

Fig.3 Arrangement of spectroscopic measurement.

of spectrum peak. From the gradient of Boltzmann plots, plasma temperature was calculated. This is according to the Line Pair Method under the condition of LTE as follows.

$$\ln\frac{I_{nk}\lambda_{nk}}{A_{nk}g_n} = -\frac{1}{kT}E_{nk} + \ln\frac{Nhc}{Q(T)} \qquad (1)$$

λ : wavelength (nm) I_{nk} : measured relative intensity
T : plasma temperature (K) A_{nk} : Einstein transition probability(s^{-1}) g_n: constant for the upper energy level
N : number density (1/m^3)   h : Planck's constant 6.63×10^{-34} (Js)
c: velocity of light E_{nk}: upper energy level (J)
k : Boltzmann's constant 1.38×10^{-23} (J/K)

The subscript n and k represents the upper and lower energy levels, respectively. The intensity of the continuous spectrum was excluded from the relative intensity [11,12].

3. Results and Discussion

3.1 Electrical Properties of Confront Electrode Type Plasma Generator

Figure 4 indicates the dependence of discharge voltage on discharge current. The main gas flow rate was 10l/min, and sub gas flow rate was 10l/min. From this result, with increasing discharge current, discharge voltage decreased from 58V to 52V, and when the discharge current became over 18A, the discharge voltage reached an almost constant value of 52V. This tendency is quite similar to the typical characteristics of an arc discharge. When the discharge current became under 10A, the plasma jet disappeared. So, I=10A was limit of discharge with this condition.

Figure 5 indicates the dependence of input power on discharge current. With an increase in discharge current, input power increased linearly. When the current was 25A, the maximum current of power supply, input power was about 1.3kW. And, at 10A, the limit of discharge current, the input power was about 650W.

Figure 6 shows the dependence of the plasma jet width on discharge current. These were measured at a distance of 3cm from the edge of anode by CCD camera. The FWHM was measured when the current was 10A, 17A and 24A respectively. As the result, with decreasing current, the width of the plasma jet became small. When the current was 25A, the maximum width was w=3.94(mm). On the other hand, the minimum width w=2.27(mm) was measured at I=10A. With a decrease in the width of the plasma jet, the radiant intensity also decreased.

3.2 Relation of between Discharge Voltage and Working Gas Flow Rate

Figure 7 indicates the dependence of discharge voltage on main gas flow rate and sub gas flow rate. With increase each gas flow rate (main and sub),

discharge voltage increased. This is because a higher energy is necessary to get larger amounts of gas into excited states. When the discharge is unstable, the discharge voltage becomes higher, in general. This measurement revealed that the ratio between main and sub gas flow rates influences the stability of the arc discharge.
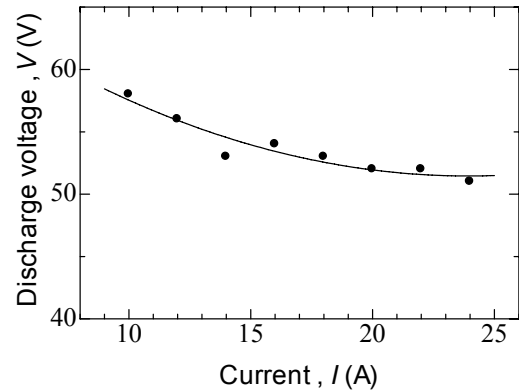

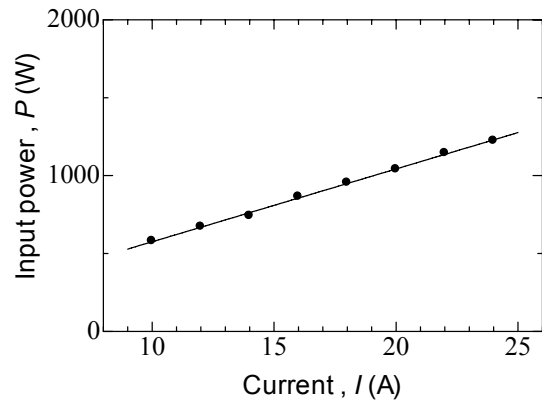**Fig.4** Dependence of discharge voltage on discharge current.

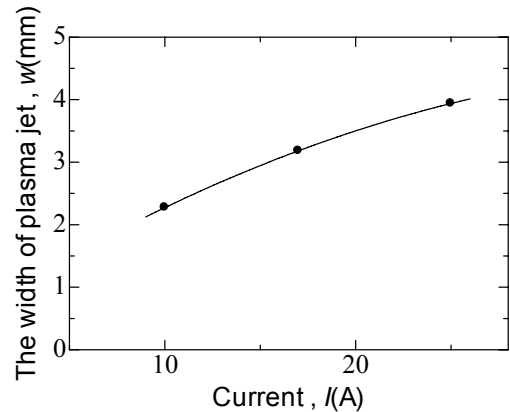**Fig.5** Dependence of input power on discharge current.

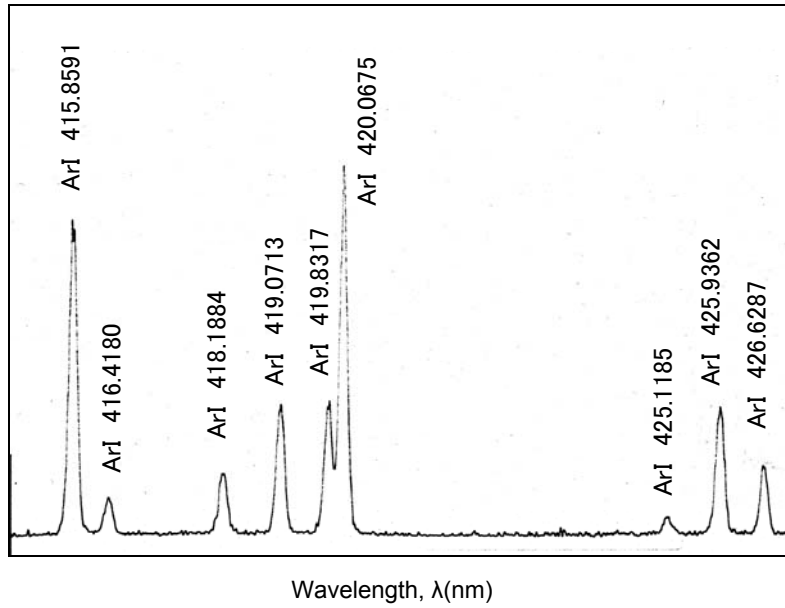**Fig.6** Dependence of the plasma jet width on discharge current.

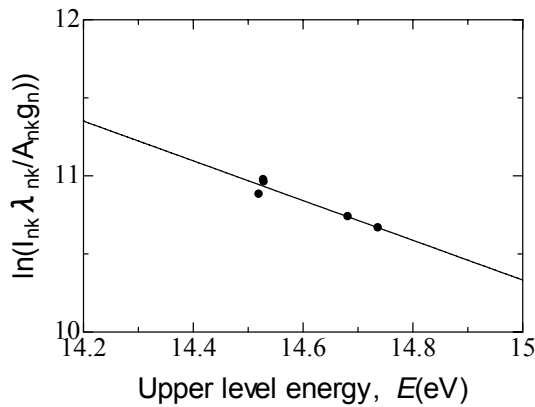**Fig.8** Measured spectrum. All of the peak was identified as ArI peak.

Fig.9 Boltzmann's plot of spectrum on 24A plasma.

Table2 Temperature of plasma jet at different positions under the following condition;I=20A,Q_{main}=Q_{sub}=8(l/min)**.**

Distance from the anode(mm)	Temperature(K)
$\fallingdotseq 0$	7500
20	5600

3.3 Temperature of Plasma Jet

The position for spectroscopic measurement was located near the anode, because at this point the strongest intensity was measured and the high speed camera showed arc stability.   In this case, the discharge current was 24A, main and sub gas flow rate were 4l/min, 6l/min respectively.

Figure 8 indicated the measured spectrum.   All of the spectrum peaks were identified as the ArI peaks.   ArII peaks were not found.   From the ArI database (NIST Atomic Spectra Database), the Bolzmann plots were obtained by the relative intensity as shown in **Figure 9**.   From the gradient of the plots, the plasma temperature was calculated.   As a result, the plasma temperature was found to be about 8,000K.   This temperature is not so high among those of conventional plasma generators, because of the lower power.   **Table 2**

shows the other result of temperature measurement under different conditions.

4. Conclusion

In this study, the fundamental characteristics of a new type plasma generator were investigated and the following results were obtained.

(1)   The electric properties of the confront electrode type plasma generator are quite similar to those of the general arc discharge, and the properties showed the dependent characteristics within the range of discharge current in this study.   In addition, with increasing discharge current, input power increased.

(2)   The plasma jet width calculated from FWHM of the radiant intensity depends on the discharge current. With increase in the current, the plasma jet width

and the radiant intensity also increased.
(3) With increase in gas flow rate, the discharge voltage also increased. It seemed that the discharge stability depends on the ratio of main gas flow rate to sub gas flow rate.
(4) By spectroscopic measurement, the temperature of the plasma jet was calculated. The result showed that the temperature of plasma jet near anode was about 8,000K when I=20A.

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