Pressure Distribution and Basic Properties of Gas Tunnel Type Plasma Jet Torch†

Yoshiaki ARATA*, Akira KOBAYASHI** and Yasuhiro HABARA***

Abstract

The basic characteristics of a gas tunnel type plasma jet which is ejected into the open air are experimentally investigated. To clarify the properties of the gas tunnel along the center axis, the pressure in the vortex chamber of the torch is measured in the absence of the plasma jet.

The pressure in the gas tunnel is a very low of 200 Torr along the center axis with a gas divertor nozzle 4–8 mm in diameter. The plasma jet produced in this low-pressure gas tunnel is longer than a conventionally-produced jet and has superior characters as follows. It has an extremely positive volt-ampere characteristic, and very high potential gradient, such as 40 V/cm at 400 A when a gas divertor nozzle 4 mm in diameter is used.

KEY WORDS: (Plasma Jet) (Gas Tunnel) (Vortex Flow) (Pressure Distribution) (High Energy Density)

1. Introduction

Plasma beam is a high energy density heat source. The plasma jet, which is ejected into the air through a nozzle from the area of electrical discharge within the torch, easily produces a high energy density and a high temperature. In addition, the conversion of electrical energy into heat energy is highly efficient. As a result, plasma beams have been widely used in such materials processing fields[1,2] as welding, cutting and coating. If a higher powered plasma jet could be developed, it would be possible to increase productivity in a large number of fields while reducing production costs. High-powered plasma jets could even be extensively applied in such new fields as melting and refining,[3] chemical synthesis[4] and decomposition, etc.

In order to produce a plasma beam of sufficiently high power, energy density and temperature, has been investigated the unique electrical discharge, i.e. plasma beam in a gas tunnel produced by means of a special vortex flow with the working gas of a big flow rate. This method is characterized by the fact that the working gas ejected through the special vortex generator nozzle rotates at higher velocity as it flows into the center, and the velocity achieves to the speed of sound around the axis, generating a low-pressure vortex gas tunnel along the center axis.[5,6] This gas tunnel is surrounded by a gas wall which has a sharp pressure gradient in the radial direction and gives a thermal pinch effect on the plasma beam produced inside the tunnel. The plasma in the gas tunnel is stable and has both a high temperature and a high energy density.[7] The gas tunnel discharge was then applied to the generation of this plasma jet.[8] This torch is expected to be applied to high-speed processing, high-temperature materials processing including melting and refining, plasma chemistry, and other related fields.

In this paper, the basic characteristics of this type torches located in the open air are investigated and discussed prior to putting them into practical application. In particular, the volt-ampere (V-I) characteristics of the plasma jet, the gas pressure distribution within and around the gas tunnel, and the dimensions of the plasma jet are

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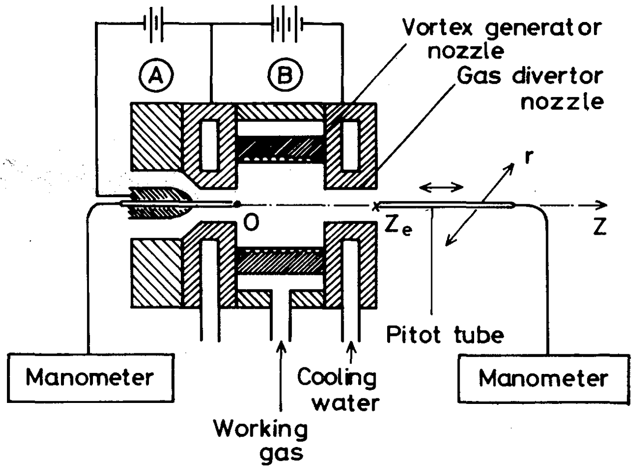


Fig. 1 Schematic diagram of experimental apparatus.

measured and discussed.

2. Experimental Apparatus and Method

Experimental arrangement of the gas tunnel type plasma jet torch is shown in **Fig. 1.** (A) is a plasma jet gun which is installed for igniting a gas tunnel discharge. (B) is the gas tunnel type plasma jet torch. This torch has been reported in detail.[8] In this work, the diameter of gas divertor nozzle '*d*' is 4 mm or 8 mm. This nozzle is located at the exit of the plasma jet torch and plays as an electrode (cathode).

The pressure distribution of a gas tunnel which is produced by the vortex generator nozzle was measured at many points in the radial or axial direction, using Pitot tube whose inner diameter is 0.6 mm and a manometer. Pitot tube was setted in parallel with the axis Z as shown in Fig. 1. This measurement was carried out in case that plasma did not exist and argon was used as the working gas. The pressure distributions were measured in the radial direction at the exit of the gas divertor nozzle and in the Z direction at the center axis of the gas tunnel.

The plasma jet is produced in a gas tunnel on the center axis of torch. The working gas is Ar. The dimensions of plasma were investigated by means of the photograph, changing the current or the gas flow rate. The length and diameter of plasma were determined by the size of the highly luminous white core flame.

3. Results and Discussion

3.1 Pressure distribution in the gas tunnel

To study the pressure characteristics of a gas tunnel produced along the center axis of the torch, the pressure p_0 was measured at the point; $Z=0$, $r=0$ shown in Fig. 1. Effects of the working gas flow rate on the pressure p_o are shown in **Fig. 2**. In this case, Pitot tube was put from anode part so as not to disturb the working gas flow. The

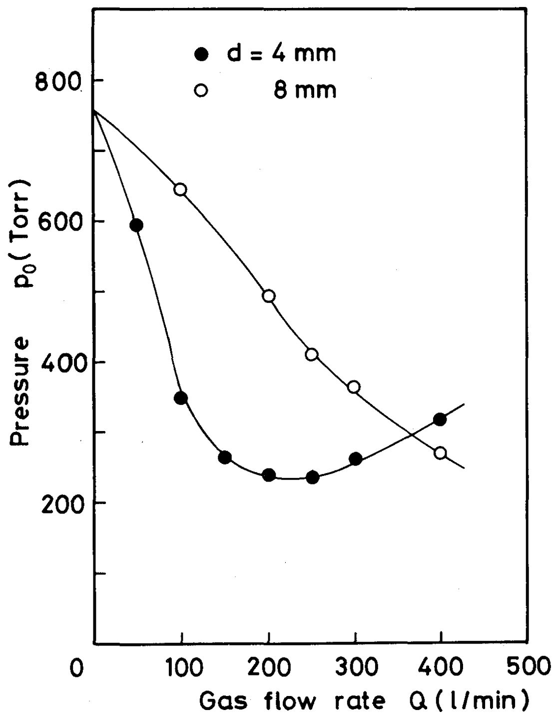


Fig. 2 Dependences of pressure at Z = 0 in gas tunnel on gas flow rate.

gas divertor nozzle diameter '*d*' is 4 mm or 8 mm.

In case of d = 4 mm, the pressure p_o at the center axis inside a gas tunnel decreases with the increase of the gas flow rate, while the pressure p_o increases at the gas flow rate over 250 ℓ/min. Because, so called "Choking phenomena" is generated when the nozzle diameter is so small and the gas flow rate is too much, as the result, the pressure in the vortex chamber becomes higher. The pressure p_o in the gas tunnel is a minimum value, 230 Torr at the gas flow rate of 200–250 ℓ/min. In case of d = 8 mm, the pressure p_o decreased with the increase of gas flow rate, and in the range of measurement, the choking phenomena didn't arise such as d = 4 mm. The pressure p_o is 270 Torr at gas flow rate of 400 ℓ/min.

The distribution of pressure in the radial direction was measured at the torch exit ($Z = Z_e$ in Fig. 1), putting Pitot tube in axial direction from the exit. The result is shown in **Fig. 3**. The gas flow rate of both nozzles is 250 ℓ/min at which the center pressure p_e was minimized in case of d = 4 mm. Low pressure gas tunnel is produced along the center of the torch and is surrounded by the high pressure gas wall. The center pressure in case of d = 4 mm is lower than that in case of d = 8 mm. Gas tunnel diameter in case of d = 4 mm is smaller than that in case of d = 8 mm. The center pressure of gas tunnel is low value of 260 Torr at d = 4 mm, 560 Torr at d = 8 mm. As these results, the plasma can be easily ionized in the center of low pressure and be stable by means of the high pressure gas wall at the circumference.

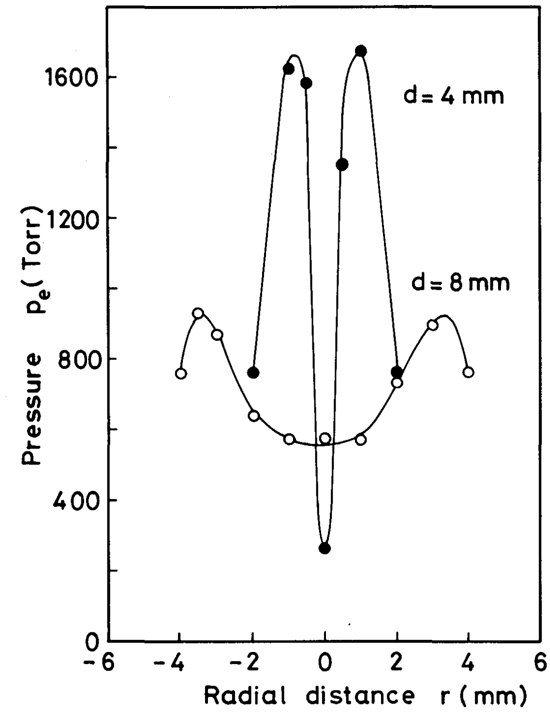


Fig. 3 Pressure distributions in the radial direction at the plasma torch exit ($Z = Z_e$), Q = 250 ℓ/min.

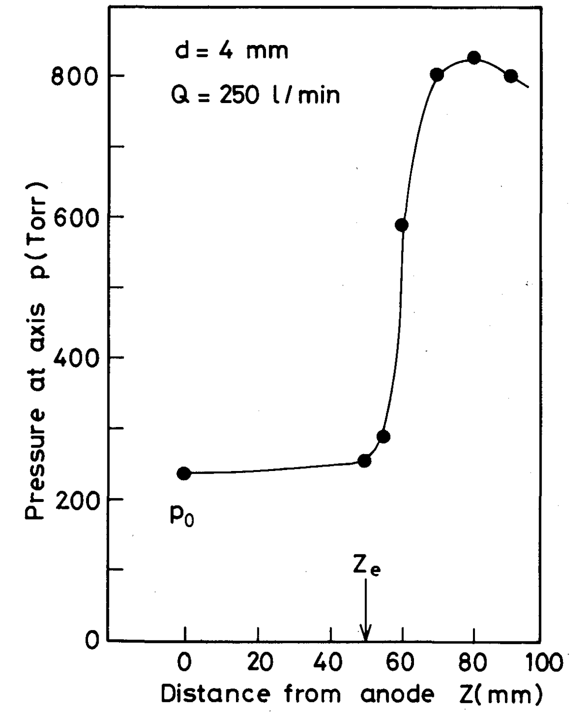


Fig. 4 Pressure distribution along the center axis (d = 4mm).

The center pressure distribution in Z direction is shown in **Fig. 4** in case of d = 4 mm, when the gas flow rate is 250 ℓ/min. A low pressure gas tunnel is produced along the center axis inside the torch, but the pressure increases gradually as Z increases outside the torch and when Z is more larger, the pressure at the axis equals to atmospheric pressure. However, the center pressure within

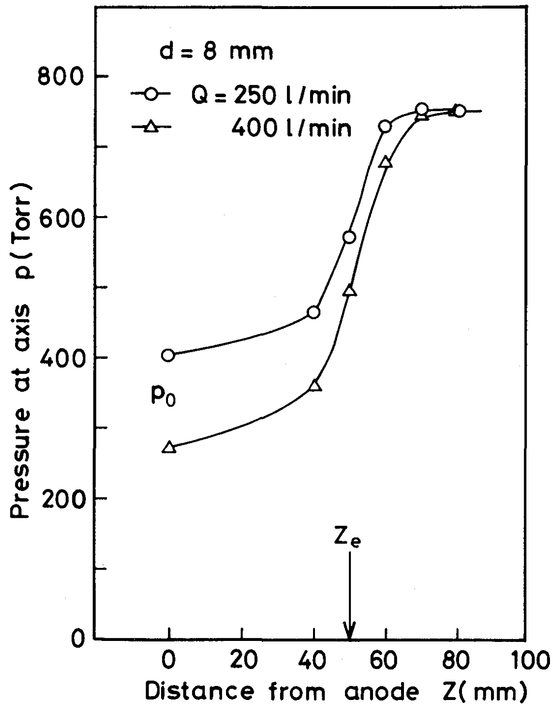
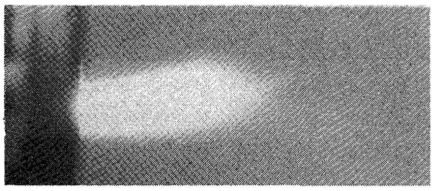
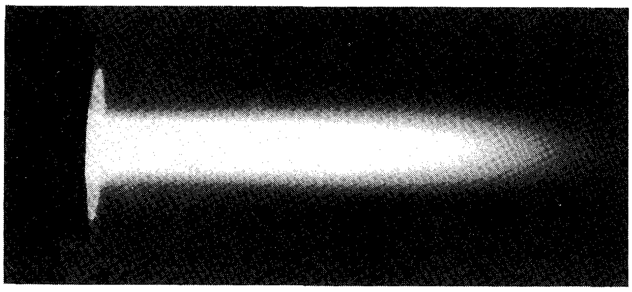


Fig. 5 Pressure distributions along the center axis (d = 8 mm)



(a) Conventional type; I=500A, d=8mm, Q=50ℓ/min.



(b) Gas tunnel type; I=500A, d=8mm, Q=400ℓ/min. 10 mm

Fig. 6 Photographs of plasma jets

about 2 cm from the torch exit is still lower than an atmospheric pressure.

Figure 5 shows the center pressure distribution in case of d = 8 mm. The results have the same tendency in case of d = 4 mm. The distribution was also measured at the gas flow rate 400 ℓ/min. In this case, a lower pressure gas tunnel could be produced effectively.

3.2 Properties of the gas tunnel plasma jet

Gas tunnel plasma jet is shown in **Fig. 6** compared with conventional plasma jet (of plasma coating device). Both the currents are the same 500 A and the nozzle diameters are both 8 mm. As shown in Fig. 6, the shape of each jet is different clearly. In the conventional plasma jet, the jet length is shorter, 20 mm, and the shape is not symmetrical. But in this gas tunnel type, the jet is ejected straightly and stably, and the jet length is very long, 50 mm. Because the gas tunnel was created efficiently along the center axis in this new type torch.

In case of d = 8 mm, the plasma jet length is increased linearly as the current increases.[8] The length was also measured in case of d = 4 mm at 100–500 A and the same characteristics was obtained. The length is about the same as that in case of d = 8 mm at the same current. In this study, the effect of jet length on the gas flow rate was measured and shown in **Fig.** 7, when the nozzle diameter is 4 mm and the current is 200 A. As the gas flow rate increases, the plasma jet length slightly increases. On the other hand, the jet diameter is almost the same as the nozzle diameter.

Figure 8 shows the volt-ampere characteristics of a gas tunnel plasma jet. The gas divertor nozzle diameter is 4 mm or 8 mm. In case of d=8 mm, the V-I characteristic had already been reported at gas flow rate 400 ℓ/min.[8] Adding this result, that in case of d = 4 mm is shown at gas flow rate 250 ℓ/min. The voltage in case of d = 4 mm is higher than that in case of d = 8 mm. Those V-I characteristics of this developed torch have positive ones shown in Fig. 8, while the V-I characteristic of a conventional plasma jet has generally a drooping characteristic. The electrical potential gradient of a gas tunnel plasma beam is estimated to be 41 V/cm in case of d = 4 mm and 33 V/cm in case of d = 8 mm at the current level of 400 A, calculated with the discharge length neglecting the voltage of the cathode and anode drops. This positive characteristic and the high voltage are due to a thermal pinch effect of the strong vortex generated by a vortex generator nozzle. The plasma jet ejected through the nozzle of d = 4 mm is more constricted, and the electrical potential gradient becomes greater.

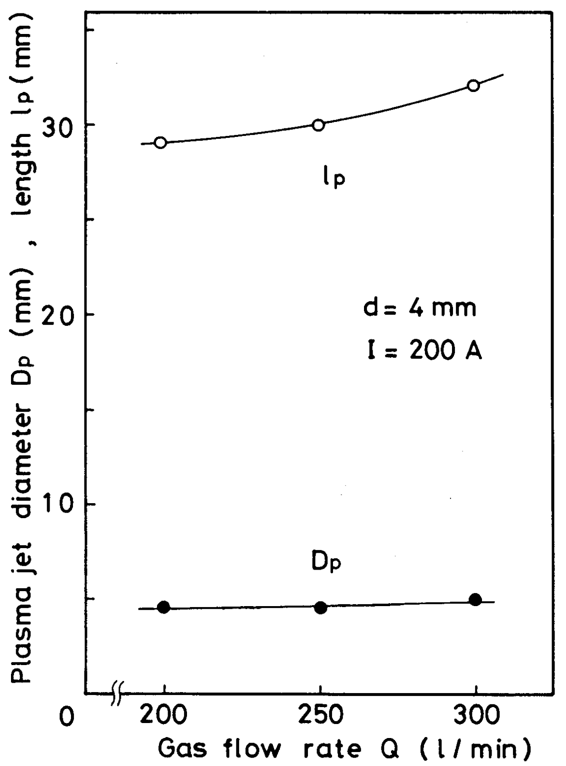


Fig. 7 Dependences of plasma length and its diameter on gas flow rate

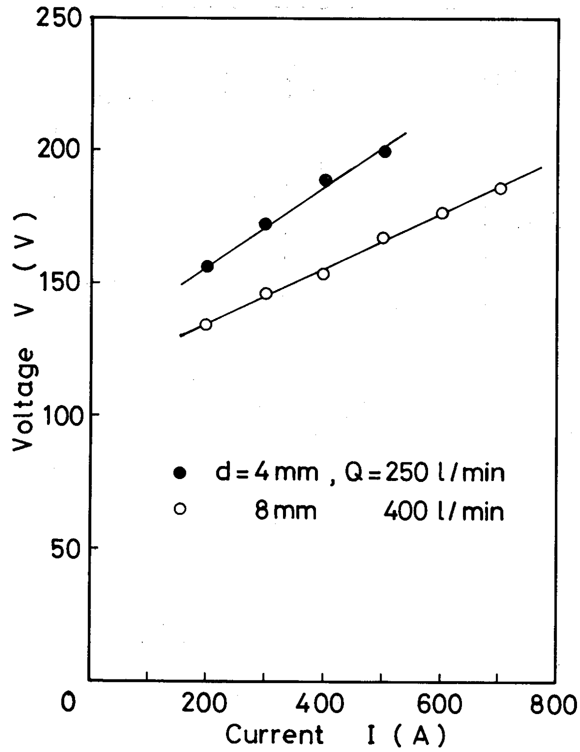


Fig. 8 V-I characteristics of a gas tunnel plasma jet

The heat energy per square unit, which is ejected through a gas divertor nozzle, was calculated with the obtained V-I characteristics and the heat efficiency of the torch, where the value of 80% was used as the heat efficiency.[8] At current level of 400 A, the mean energy density at the torch exit is $1 \times 10^5 W/cm^2$ in case of d = 8 mm, while in case of d = 4 mm, the value is about $5 \times 10^5 W/cm^2$, as a higher power energy was ejected through the nozzle of a small diameter. The energy density of this plasma jet itself seems to be more higher than the mean value, i.e., more than $10^6 W/cm^2$, because of being surrounded by the gas wall of cold temperature.

The spectroscopic measurements[9] of a gas tunnel plasma jet have been carried out at the torch exit. **Figure** 9 shows the profiles of ArII spectral lines (480.6nm, 488.0nm). Thus, ArII spectral lines are observed clearly as shown in Fig. 9.

The influence of the sort of the working gas on the voltage of a plasma jet has investigated, and it is evident that a thermal pinch effect of the working gas is greately affected by the ionization energy and dissociation energy and so on. Therefore, a higher powered plasma jet could

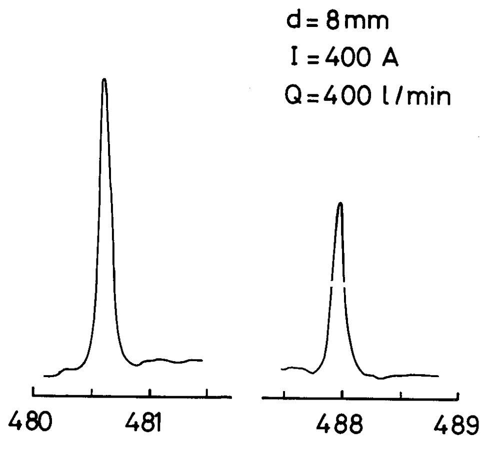


Fig. 9 Intensity profiles of spectral lines observed at the exit of plasma jet torch

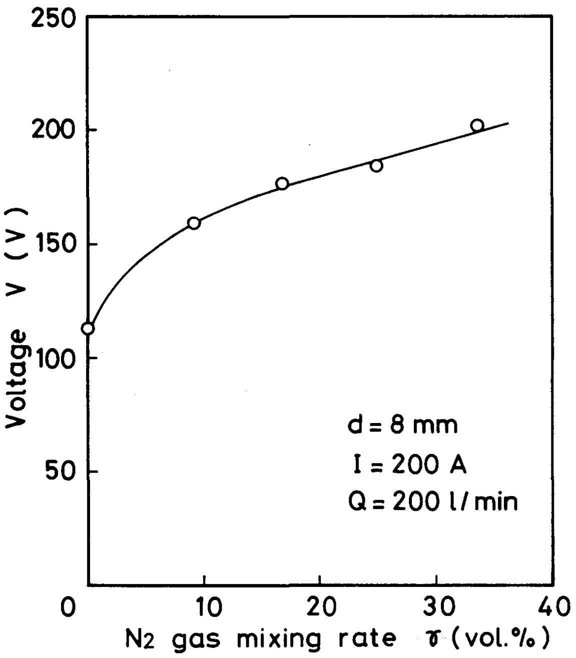


Fig. 10 Dependence of voltage on N_2 gas mixing rate in Ar gas

be produced by the selection of working gas. In this type of plasma jet, the mixing gas of Ar and N_2 was used as the working gas, and the effects of N_2 gas on the voltage were measured. **Figure 10** shows the dependence of the voltage on N_2 gas mixing rate 'γ' in Ar gas, when the total flow rate of working gas is 200 ℓ/min and the current is 200A. The voltage of plasma jet is remarkably influenced by the large dissociation energy of nitrogen. The voltage is raised with the increase of N_2 gas mixing rate and is 203V at $\gamma = 34\%$. The effect appears more significantly when the mixing rate is less than 10%.

4. Conclusion

In this study, we clarified through experiment some of the basic characteristics of a gas tunnel type plasma jet. The results of this study are as follows:

1) The pressure in the vortex chamber of the gas tunnel type plasma jet torch was measured in the absence of the plasma jet. The gas tunnel can be produced effectively inside this torch.
   i) The pressure inside the gas tunnel is very low 200 Torr along the center axis when the gas divertor nozzle is 4−8 mm in diameter.
   ii) Even outside of the torch, the effect of gas tunnel is very strong.
   iii) When the diameter of the gas divertor nozzle is small, the pressure at the center axis is rather low, but the gas tunnel has a smaller diameter and the gas flow through the gas divertor is choked.
2) The resulting gas tunnel plasma jet is longer than a conventional type of jet. This plasma jet has a positive V-I characteristic, and the potential gradient is greater than 40 V/cm at 400A when the gas divertor nozzle is 4 mm in diameter.
   i) A very long plasma jet can be obtained.
   ii) The gas tunnel plasma jet produced in this way has a higher energy density. The spectra of ArII could also be clearly measured.

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