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"Fundamental Characteristics of Stationary Plasma Arc in Gas Tunnel"†

Yoshiaki ARATA* and Akira KOBAYASHI**

Abstrast

The stationary plasma arc in gas tunnel has been investigated and the characteristics are clarified experimentally.

At first the mechanism of the formation of gas tunnel by strong vortex flow with big flow rate was studied theoretically. And on the pressure distribution in the vortex chamber, the results showed good agreement with the experimental results in the annular region of the vortex chamber.

The plasma arc produced in this gas tunnel has high temperature and high electron density as compared with conventional plasma arc, because of strong thermal pinch effect. The characteristics of this plasma arc has been mainly carried out by spectroscopic measurement. As the result almost fully ionized plasma has been obtained in gas tunnel at even small current of 200 A, by means of shortening the vortex chamber length.

KEY WORDS: (Plasma Arc) (Vortex Flow) (Pressure Gradient) (Stationary) (Fully Ionized)

1. Introduction

Study on plasma arc at an atmospheric pressure has been done by many workers up to this time[1,2]. And, for the stabilizing methods of plasma arc are used a lot of kind of methods including gas rotation[3], water stabilizing[4], wall stabilizing[5] and so on. Now, among those methods, the stabilization by gas rotation is most popular[6]. But on the conventional method, the flow rate of the working gas is a little (about 50 ℓ/min) and the pressure gradient of radial direction in the cylindrical chamber is small, and the influence of the pressure gradient on plasma has not been investigated in detail.

On the other hand, in this study, by gas jet having big flow rate, more than 300 ℓ/min, from fine nozzles, a strong vortex flow is formed in the cylindrical chamber. And using gas divertor nozzles at both ends of the chamber, the pressure-wall having sharp pressure gradient in radial direction is produced. The pressure at the center region surrounded by the pressure-wall is very low and the region was named vortex gas tunnel or "gas tunnel"[7,8]. In this gas tunnel, plasma arc is produced and investigated in detail. By this method, two effects are given to plasma arc. One of them is that the ionization of the working gas is easy due to the low pressure in the center region, and the other is that the stability of plasma beam is improved remarkably by the sharp pressure gradient in the radial direction.

Therefore, in this study, the mechanism of the formation of "gas tunnel" produced in the center region of vortex flow having sharp pressure gradient is clarified. And the characteristics of the plasma arc in the gas tunnel are investigated experimentally. In addition, for the purpose of production of stationary fully ionized plasma beam whose temperature is more than a few ten thousands Kelvin degree, the experiment has been carried out by means of the increase of electric input.

2. Mechanism of Formation of Gas Tunnel

In this section the mechanism of the formation of the vortex gas tunnel has been investigated theoretically and experimentally.

In the case that the gas as fluid is moving as vortex motion in the cylindrical chamber, two models which are shown in **Fig. 1** have been considered in this study. One of those is ordinary type of vortex motion, "model I", so called "forced vortex". And the other is vortex motion, "model II" which has a strong sink in the center axis of the vortex chamber[9].

In model I, by the viscosity of the fluid, the gas rotates with a constant angular velocity from the chamber wall to the center, as a rigid body. Then the pressure distribution in the chamber is presented as follows[9].

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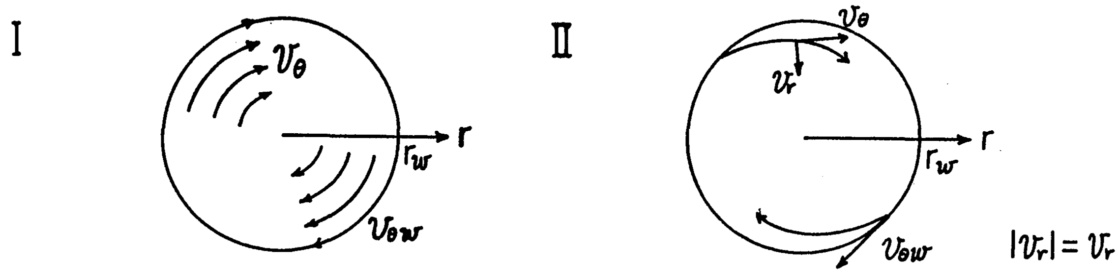

Fig. 1 Two models of vortex flow in the cylindrical chamber, where I is "model I" and II is "model II".

$$\frac{p}{p_w} = \exp\left[\frac{1}{2}\frac{v_{\theta w}^2}{RT}\left\{\left(\frac{r}{r_w}\right)^2 - 1\right\}\right] \qquad (1)$$

where p is pressure, p_w is the pressure at the chamber wall, $v_{\theta w}$ is the velocity in the tangential direction at the wall, r is radius, r_w is the radius at the wall, R is gas constant, and T is temperature.

On the other hand, in the case of the vortex flow of model II, the gas is drawn into the sink in the center of the chamber and therefore, the radial velocity is generated. Here, the viscosity of the working gas can be neglected. And, the pressure distribution is presented by the following equation[9].

$$\frac{(p/p_w)^2 - (v_{rw}/v_{\theta w})^2}{1-(v_{rw}/v_{\theta w})^2} \doteqdot \exp\left[-\frac{1}{2}\frac{v_{\theta w}^2}{RT}\left\{\left(\frac{r_w}{r}\right)^2 - 1\right\}\right] \qquad (2)$$

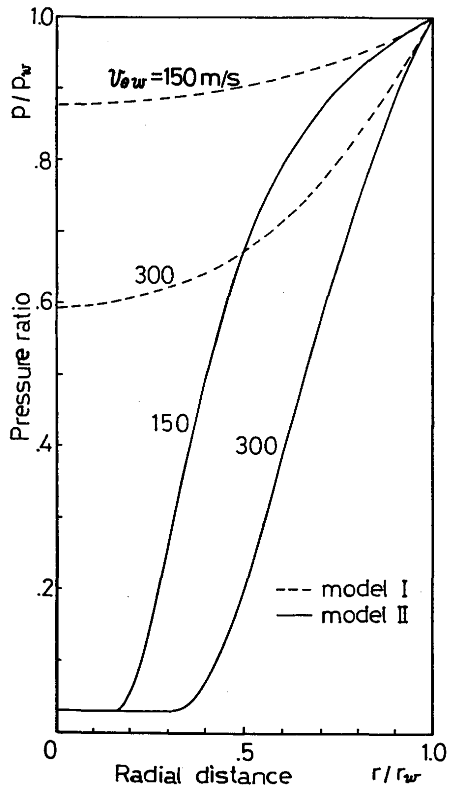

Fig. 2 Theoretical pressure distributions in the radial direction

These theoretical results of the both models are shown in **Fig. 2**. Thus, the characteristics of the two models, model I and model II, are very different each other. In model I, the pressure distributions are like a parabola, and those bottoms are broad. But, in model II the pressure gradient is very sharp, besides the pressure of the center p_o is very small value. Anyway, in both types, the pressure gradient is sharper in the annular region, as the gas velocity at the wall is higher.

In order to realize these two types of vortex flow, the simple experiments are carried out using two types of the

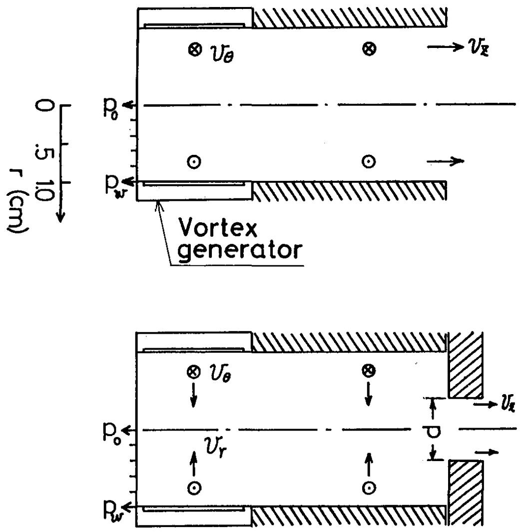

Fig. 3 Experimental apparatus for realizing two types of vortex flow, model I and model II

apparatus shown in **Fig. 3**. The diameter of cylindrical chamber is 20 mm, and the length is 40 mm, respectively. And vortex generator is located at the chamber wall. Air, the working gas, flows into the chamber in tangential direction from the vortex generator, and forms vortex flow in the chamber. The one side of the chamber is closed and the pressure is measured at these side points. In model I, the other side is open, but in model II, there is a nozzle called gas divertor nozzle.

The results in model I are shown in **Fig. 4**. This shows that the velocity at the wall is 150 m/s. In comparison with theoretical results, experimental data of pressure appear a little high in the center region, and the velocity v_θ is different from constant angular velocity. But the characteristics of pressure distribution show good coincidence with theoretical result.

In **Fig. 5** the results of experimental pressure distribution in the case of model II are shown. Those plots show experimental data, where each diameter of gas divertor nozzle is 13 mm, or 6 mm. Those curves shown by dotted lines, are good coincidence respectively with theoretical line in the annular region. In the case of small diameter of gas divertor nozzle, $v_{\theta w}$ is small value, and the coincident annular region becomes larger. In this case, the value of

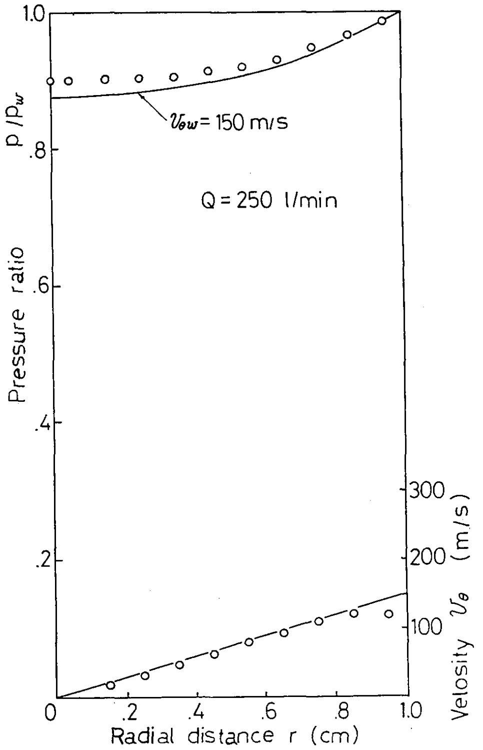

Fig. 4 Experimental pressure distribution in model I

the pressure at the axis is very small, and this low pressure region including the axis, surrounded by the gas wall having large gradient has been named "vortex gas tunnel" or simply "gas tunnel" as already described.

In **Fig. 6**, the each pressure at the center axis and the wall of the chamber is shown corresponding to gas flow rate. Here, the diameter of gas divertor nozzle is 8 mm. As the flow rate is bigger, large pressure difference of Δp (=p_W-p_O) can be obtained. But, in the case that the pressure outside of gas divertor nozzle is an atmospheric pressure, "without pump", the gas flows into gas tunnel in the axial direction from the gas divertor nozzle. Therefore, the value of the pressure at the axis is limited, about 300 Torr in the case of 300 ℓ/min.

But, the pressure at the axis can be lower value by

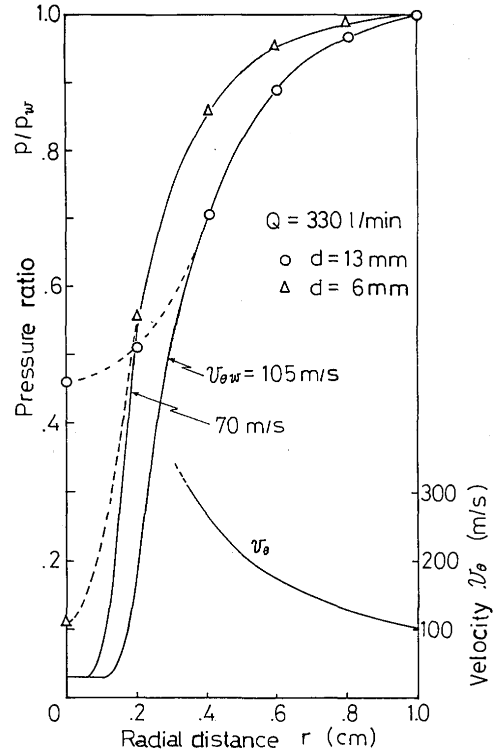

Fig. 5 Experimental pressure distributions in model II

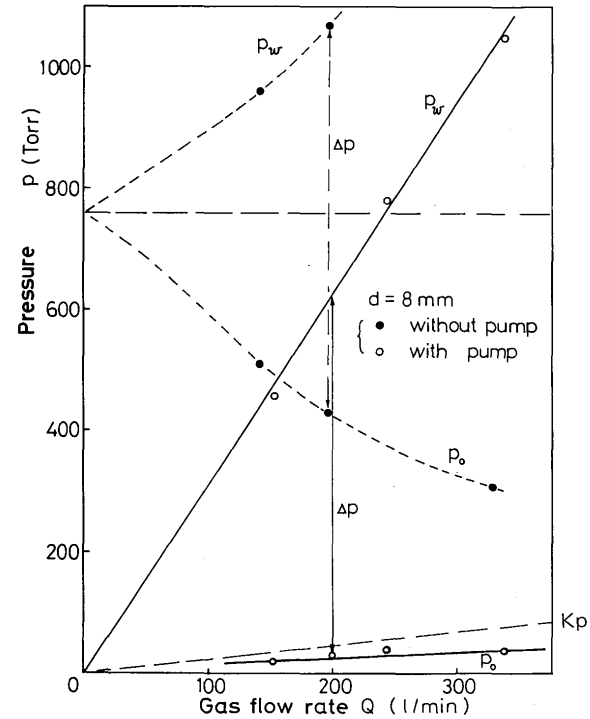

Fig. 6 Dependences of pressure in the gas tunnel upon gas flow rate

means of preventing the counter flow using vacuum pump. This case is shown in Fig, 6 as "with pump", and the pressure at the axis is about half of the capacity (characterstic line, Kp) of the vacuum pump. Besides in this case the pressure difference is almost the same in comparison with "without pump".

The typical pressure distribution is shown in **Fig. 7**. In this case, the gas flow rate is 340 ℓ/min, the diameter of gas divertor nozzle is 8 mm, and this experiment has been carried out by using a vacuum pump. The pressure at the axis is less than 40 Torr against the pressure at the wall, 1050 Torr, and the ratio p_o/p_w is about 0.04.

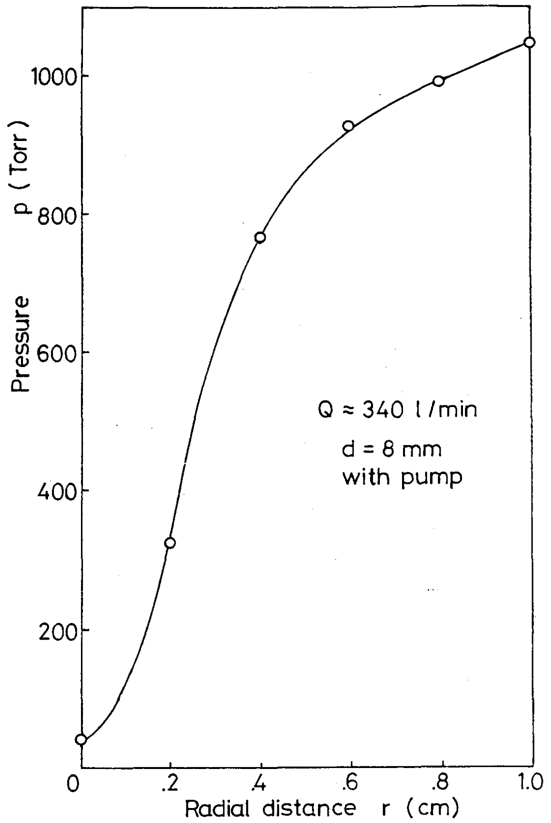

Fig. 7 Typical pressure distribution in the radial direction

These characteristics of the gas tunnel are very useful for the plasma production and stabilization, and thermal pinch of plasma arc.

3. Experimental Apparatus

The schematic diagram of experimental apparatus applied in this study is shown in **Fig. 8**. The discharge tube whose diameter is 20 mm is so called "cascade type" and constituted from seven segments insulated electrically. The "vortex generator" which supply the working gas to the chamber in the tangential direction is located at the center of the discharge tube. And at the both sides, gas divertor nozzles made of boron-nitride, whose diameter is 8 mm, are located.

We call the area which surrounded by the wall of the discharge tube and two gas divertor nozzles, "vortex chamber". The location of gas divertor nozzles can be easily changed. So for the length of vortex chamber i.e. chamber length is selected each value 7.4 cm, 3.4 cm, 1.4 cm. As the electrodes, tungsten is used for the cathode, copper for the anode. The distance between those electrodes is long sufficiently in comparison with plasma diameter. Besides, the applied power source is direct current type and the load voltage is 120 V and electric current is 500 A.

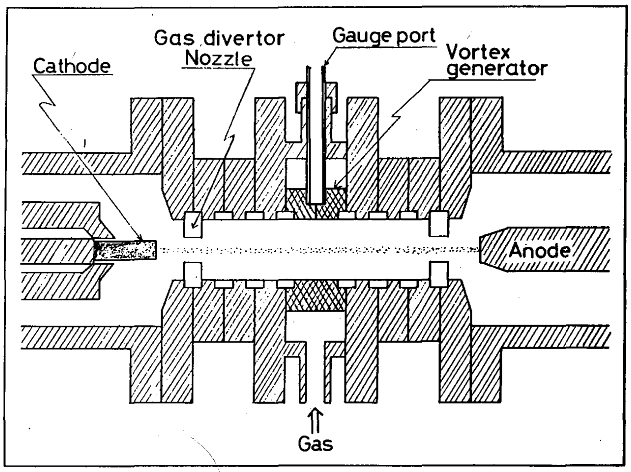

Fig. 8 Schematic diagram of plasma generator

Next we explain the concrete methods of the experiment of this study. At first, argon gas spouting in the vortex chamber through the vortex generator's nozzles forms a vortex flow with high velocity. The gas, as rotating with high velocity, is exhausted to the both outsides of the vortex chamber through the gas divertor nozzles by a vacuum pump having large capacity. Then the vortex gas tunnel at low vacuum pressure as shown in Fig. 7 is produced. At this time, the tungsten cathode is inserted in the vortex chamber, and a high-frequency discharge starts plasma arc. After production of the plasma arc, the cathode is pull out to the certain location, and the gas flow rate and electric current are adjusted proper values.

The measurement for physical parameters of this plasma has been done through the guage port and through windows located at the center of the vortex chamber. As the probes, thermocouple, pitot tube, and so on, are used in order to measure the distribution of temperature, electric potential and pressure at the region surrounding plasma. And the measurement of plasma parameter has been done by spectroscopic method, which is indicated by block diagram in **Fig. 9**. Where electron density of plasma is decided from the stark broadening of hydrogen spectral lines of Balmar series, H_α, H_β. The plasma temperature is obtained by Saha's equation assuming thermal equilibrium of the plasma, and by the relative intensity ratio of spectral lines of argon ion ArII. Besides the plasma diameter is decided by the half width of spatial distribution of ArII line intensity.

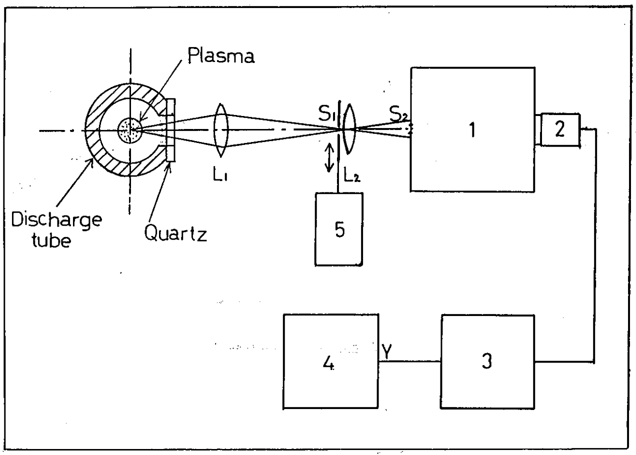

Fig. 9 Block diagram of spectroscopic measurement
1: Spectrometer, 2: Photomultiplier, 3: Amplifier,
4: X Y recorder, 5: Slit scanner

4. Production of Fully Ionized Plasma

4.1 Characteristics of plasma beam in gas tunnel

Fig. 10 shows heat losses from the plasma beam in the both cases, conventional method by gas rotation ("without gas divertor nozzle") and this method by strong vortex flow ("with gas divertor nozzle"). These measurement values are obtained by the increase in temperature of the cooling water for each segment of the plasma apparatus. In the case of "without nozzle", about 28% of the total heat loss is heat loss in radial direction. On the other hand, in the case of "with nozzle", radial heat loss is a little, and the rate against total heat loss is about 4%, very small value. This reason is that the strong vortex flow has a large radial velocity component. This velocity component remarkably suppresses radial heat loss by thermal conduction and generates strong thermal pinch effect. As the result, high temperature and high electron density plasma whose heat loss is dominated by convection, and whose diameter is very fine, has been produced.

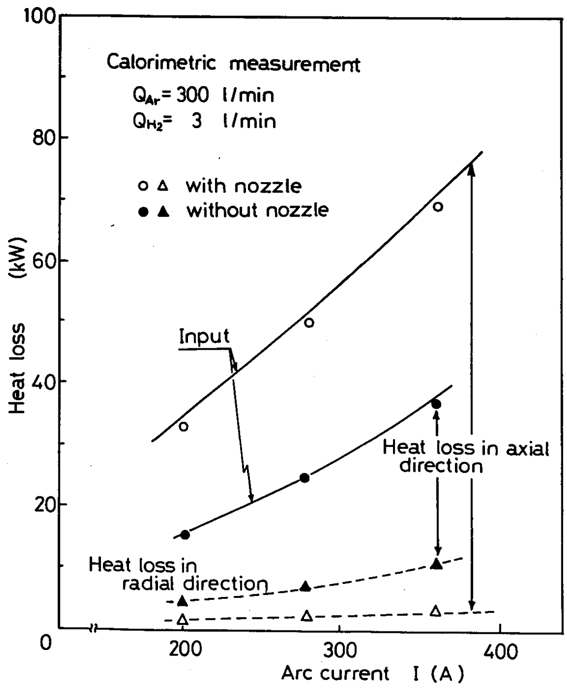

Fig. 10 Characteristics of heat loss from plasma beam

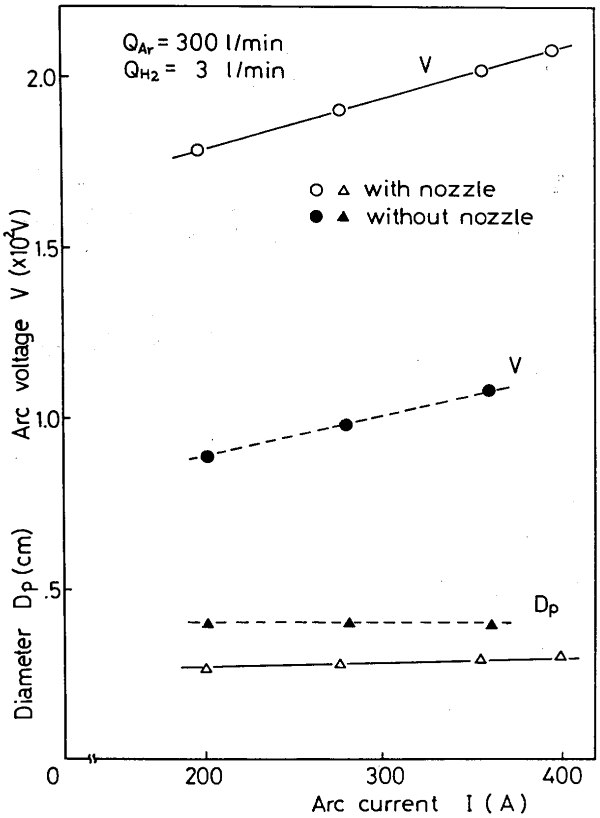

Fig. 11 Dependences of plasma diameter and arc voltage on arc current

Then, the plasma beam diameter and/or "plasma diameter" defined by the half width of spatial distribution of ArII is shown in **Fig. 11** as a dependence on electric current. It is clear that the plasma diameter in this study using the gas divertor nozzles is finer than that by means of the conventional method at the same current. At 400 A the diameter Dp is 2.5 mm. In Fig. 11, the characteristics of the arc voltage are also shown. In the case of "with nozzle", the arc voltage is about two times of that of "without nozzle".

Then, **Fig. 12** shows the comparison of plasma temperature and electron density, between the both cases. Dotted lines show the values in the case of "without nozzle", and real lines, "with nozzle". As the electric current increases, the electron density of the plasma increases in both cases, but in the latter case, the value is about two times bigger than that in the former case. And in the case of "with nozzle", the plasma temperature increases largely. This result shows that the thermal pinch effect for the plasma is stronger in the case of "with nozzle".

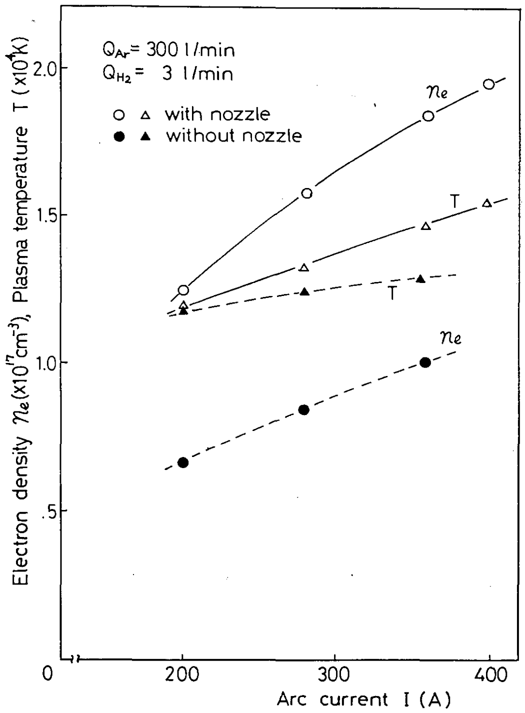

Fig. 12 Dependences of plasma temperature and electron density on arc current.

It is considered that these results are due to the strong vortex flow. So, the pressure in the region surrounding the plasma was measured by a pitot tube. The results is shown in **Fig. 13**. In the case of "without nozzle", the radial

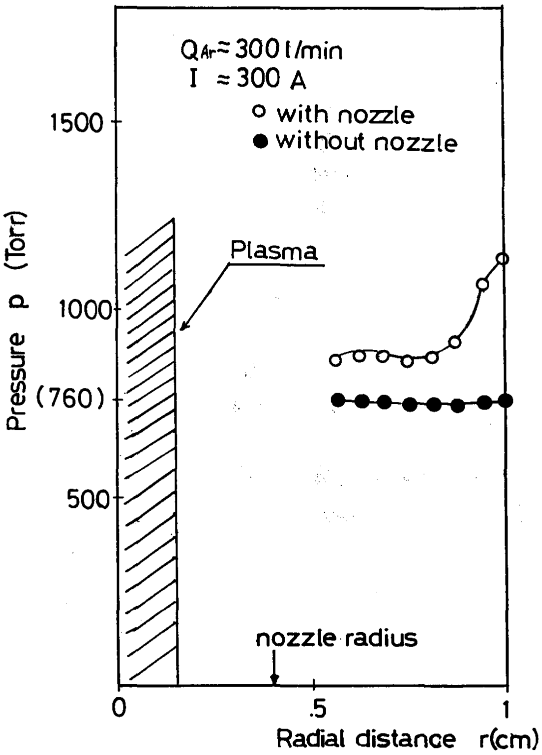

Fig. 13 Results of pressure measurement by pitot tube

pressure gradient is almost zero in the region surrounding plasma. On the other hand, in the case of "with nozzle", as shown in the same figure, the pressure gradient near the wall of vortex chamber is maintained even though plasma exists. Consequently, the plasma stability shows a good result, and the thermal pinch effect is very strong. So, plasma having high electron density and high temperature can be obtained easily.

Now, as described above, according to the increase of argon flow rate, dp/dr increases, and then the role of vortex flow for the stabilization of the plasma increases, and at the same time, the thermal pinch effect is stronger. **Fig. 14** shows the experimental results of the characteristics of the plasma parameters. At this time the electric current is a constant value, 240 A, and the flow rate of argon gas is changed in a range of 100 ~ 300 ℓ/min. According to the increase of gas flow rate, the thermal pinch effect by the strong vortex flow is stronger, and the plasma diameter gradually decreases. On the other hand, the arc voltage increases, and as the result, the electron density and the temperature of the plasma increase. Corresponding to this result, ArII intensity increases as the gas flow rate increases.

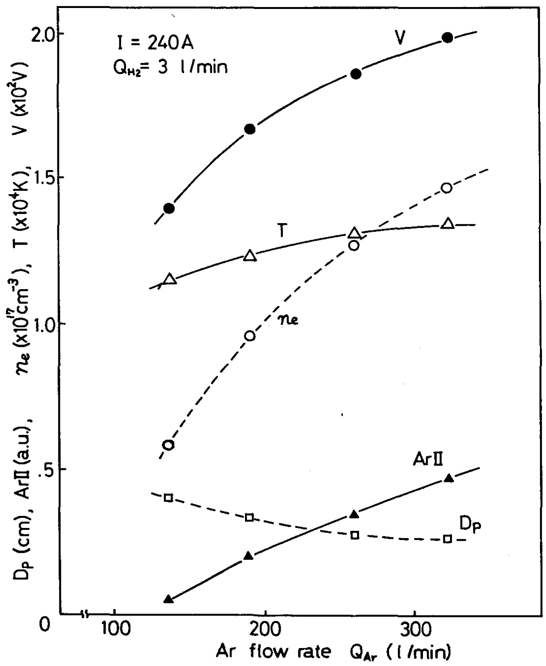

Fig. 14 Dependences of plasma parameters on gas flow rate

4.2 Influence of chamber length

Here we mention about the influence of chamber length i.e. the distance between two gas divertor nozzles, on the plasma parameters. So, the radial pressure distribution has been measured by the pitot tube in the case that plasma doesn't exist. The result is shown in **Fig. 15.** For the chamber length can be selected the values, 1.4, 3.4, 7.4 cm. The experimental results of the pressure measurement show that the shorter the chamber length is, the bigger the pressure gradient is. In this case the pressure at the center axis is not correct by means of the disturbance of the gas flow by the pitot tube. The real pressure at the center axis seems to be less than 40 Torr.

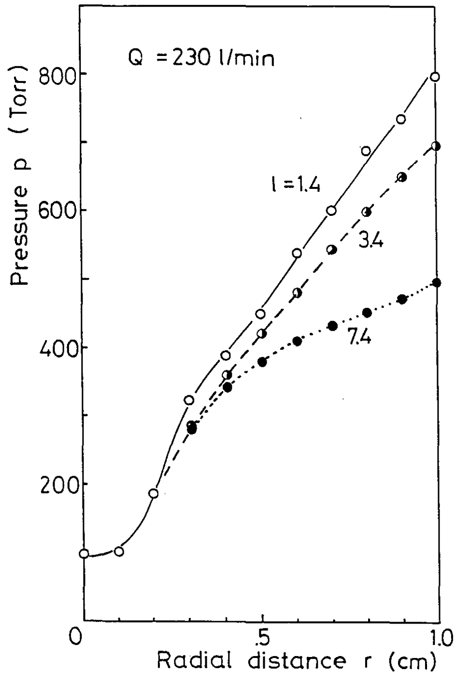

Fig. 15 Radial pressure distributions in various chamber length

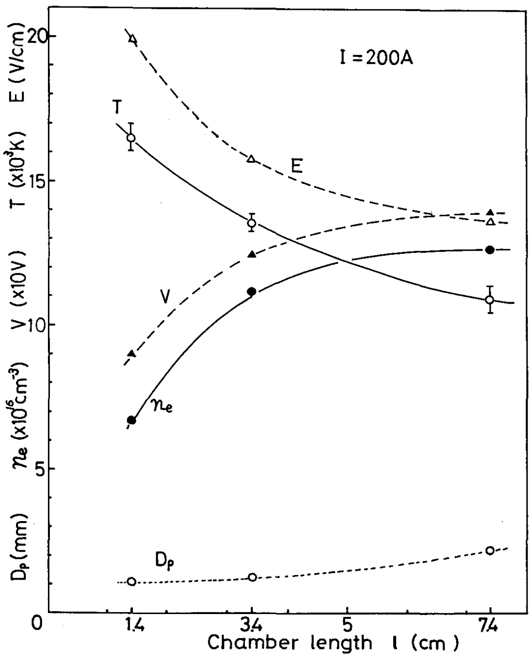

Fig. 16 Characteristics of plasma parameters against chamber length

Fig. 16 shows the characteristics of the plasma parameters for the chamber length. Here, the electric current value is constant, that is 200 A, and the distance between two electrodes is also constant, 10 cm. As the chamber length is shorter, the electric potential difference E increases, but the arc voltage decreases. Because the electric potential difference at the outside of the vortex chamber is rather small value, $4 \sim 8$ V/cm. The thermal pinch effect by the vortex flow is strong, when the chamber length is short. As the result, the plasma diameter is very fine, 1.2 mm, and the plasma temperature increases, and reaches about 17000 K in the case of 1 = 1.4 cm. On the other hand, the electron density of the plasma decreases gradually, the value is 6×10^{16} cm^{-3} in the case of 1 = 1.4 cm. Because, the shorter the chamber length becomes, the lower the pressure at the gas tunnel is, by means of the effect of the strong vortex flow.

As mentioned above, in order to obtain more stable and higher temperature plasma, the apparatus of the plasma generator whose chamber length is shorter is appropriate. Then, for instance, when the chamber length is 1.4 cm, fully ionized plasma has been produced in the gas tunnel at 200 A.

5. Conclusion

The stationary plasma arc in the gas tunnel has been investigated and the characteristics are clarified experimentally. The results obtained in this study are as follows:

(1) The mechanism of the formation of gas tunnel by the strong vortex flow with big flow rate, has been studied theoretically. And on the radial pressure distribution in the vortex chamber, the results showed good agreement with the experimental results in the annular region of the vortex chamber.

(2) The plasma in the gas tunnel has high temperature and high electron density as compared with the conventional plasma arc, because of the strong thermal pinch effect. The effect appears remarkably in the case of rather larger flow rate, and the velocity in the radial direction suppresses thermal conduction loss of the plasma.

(3) The chamber length has important role for the characteristics of the plasma parameters. As the result, almost fully ionized plasma has been obtained in the vortex gas tunnel at even small current of 200 A, when the chamber length is 1.4 cm.

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