High Power Microwave Plasma Beam as a Heat Source (Report II)†
—Characteristics of 30 kW Plasmatron—

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Abstract

Microwave plasma in a 30 kW-class plasmatron of rectangular waveguide type is experimentally investigated under atmospheric pressure. Stable nitrogen plasma is obtained up to the maximum input power level with a very small reflection of power lower than ten percents. At the input power of 20 kW, plasma beam length becomes about 35 cm and its diameter 15 mm, where the tangential gas flow rate is varied from 100 to 600 l/min. Occurence of the minimum value in the reflected power at the input power of 10 kW is observed and shift of the hottest part towards the direction of the source is seen with the increase in the power input.

Quenching of neutral atomic line in a discharge of Ar or He with a slight mixing of H_2 is ascertained experimentally, which is a unique result of microwave plasma compared with arc or induction torch.

1. Introduction

In the previous paper[1] a systematic experimental investigation was reported on a microwave plasma formed on the coaxial waveguide. With the power of about 3 kW at f=2.45 GH$_z$ a low temperature plasma of about $6 \sim 7 \times 10^3$ K was obtained and it is clarified that the plasma beam acts as if it is a matched load forming an inner conductor of the coaxial waveguide.

Based on this result we progressed on the investigation of the steady state plasma produced by a 30 kW-class microwave of f=915 MHz. Configuration of the plasmatron is changed to the rectangular waveguide type[2] to make plasma axis to be parallel to the electric line of force.

By increasing the power level various peculiarities should be taken into acount: nonequilibrium between electron temperature and gas temperature which is caused by strong electric field[3] and strong gas flow rate[4]; anomalous skin effect reported in Kapitza's paper[5], etc.. These problems are not yet studied experimentaly in microwave plasmatron at all.

Before we proceed to these problems it must be emphasized that the formation of a stable plasma at atmospheric pressure in this configuration at the power level of 30 kW is not reported anywhere as far as we know. So that production of a stable plasma beam at this power level and the research of basic qualitative characteristics of that plasma should be treated first of all.

In this paper mainly nitrogen plasma in tangential gas flow is studied experimentally and its characters are described for various external parameters-input power, gas flow rate, hydrogen mixing rate, etc.. In sec. 2 experimental apparatus and diagnostic methods are stated and Sec. 3 describes experimental results and in Sec. 4 some qualitiative discussions are given.

2. Experimental Set-up

Schematic diagram of experimental apparatus is shown in **Fig. 1.** CW microwave with f=915 MHz produced by magnetron, M propagates in a rectangular waveguide with TE_{10} mode through circulator, C, directional coupler, D and E-H tuner, T towards the

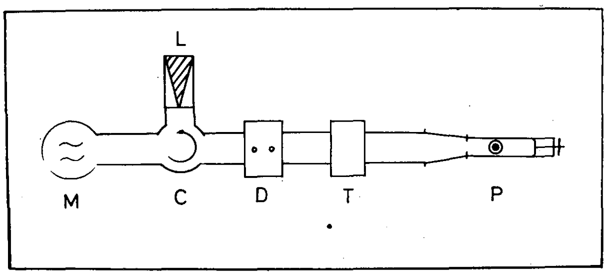

Fig. 1. Schematic diagram of experimental apparatus: M-magnetron with the maximum output power of 30 kW, CW at f=915 MHz, C - circulator, L - matched water load, D - directional coupler, T - EH tuner, P - plasmatron.

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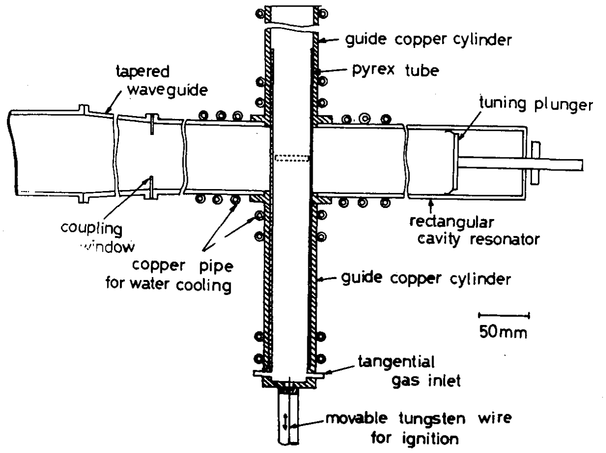

Fig. 2. Cross-sectional front-view of plasmatron.

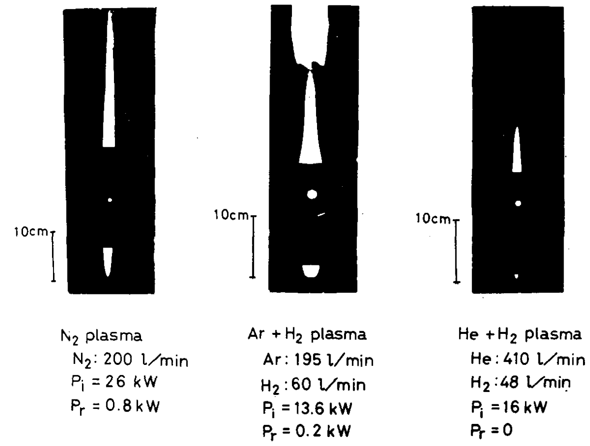

Fig. 3. Photographs of the plasma beam in various gases.

plasmatron, P, whose datailed configuration is drawn in **Fig. 2.** The wave power can be varied continuously up to 30 kW. Matched water load, L absorbs all the reflected wave from the plasma. With D the input power to the plasma, P_i and the reflected one, P_r are detected through thermister mounts. T offers the optimum matching of the wave to the plasma.

In Fig. 2 the cross-sectional front-view of the plasmatron is sketched in detail. The main part of the plasmatron is a water-cooled rectangular cavity resonator whose dimension is $180\times60\times340$ mm. A TE_{10} mode standing wave is obtained with $\lambda_g/2=17$ cm. A pyrex tube of 40 mm inner-diameter is inserted through holes on the upper and the lower wider walls of the resonator. Tangential gas flow is introduced from the bottom end of the tube. Several kinds of gas (N_2, He, Ar) and its mixture with H_2 are used in the range of the flow rate $100\leq\phi\leq 600$ l/min. To shield the microwave radiation and limit the light emission the side wall of the pyrex tube is covered with water-cooled copper cylinders, and the ignition of the plasma is performed by inserting a tungsten wire from below. Submatching of the wave is also obtained by driving a tuning plunger at the end of the plasmatron. For spectroscopic measurements a slit of 5×40 mm is cut on one of the narrower side walls of the resonator and on the other a hole of 8 mm diameter is given to show the center of the plasma beam in the axial direction as is seen in **Fig. 3.**

Optical system is similar to the one in Ref. 1). Spatial distribution of monochromatic light emitted from the plasma beam is obtained with a monochrometer of 0.25 m Ebert-type whose first order dispersion is 33 Å/mm. Plasma diameter is estimated from half width of radial distribution of emitted light. Meanwhile plasma length is obtained by photographic method. In this case, of course, the guide copper cylinders are removed. It is experimentally ascertained that the removal of this cylinder gives no change in the plasma configuration.

3. Experimental Results

In Fig. 3 typical photographs of the plasma beam are shown for various gases. In this figure only a part of the guide cylinders is set and white spots indicate the center of the plasma beam in the axial direction. The plasma beam is quite stable and easily reproducible. Moreover the reflection of microwave is very small even at a high power of about 20 kW. It can be said that the plasma beam behaves as a well matched load to the wave. The difference in the discharge profile for various gases is quite similar to the one reported in the previous paper[1]. Especially as is seen in Fig. 3, the more the percentage of H_2 in He or Ar, the more stable are the plasma and the power input can be increased to a larger one.

Fig. 4 is the dependence of the reflected power,

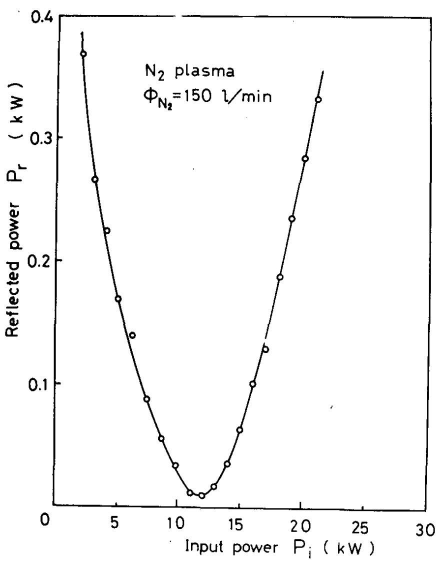

Fig. 4. Dependence of the reflected power on the input power in N_2 plasma. External matching is always undertaken with EH tuner for each input power.

P_r on the input power, P_i in N_2 plasma. External matching with EH tuner is always undertaken for each input power to minimize the reflection of the wave. This curve indicates that the most favorable matching to the plasma is achieved near $P_i = 10$ kW and at a lower or a higher power the reflection increases, though of course its absolute value is quite small (lower than 10 %). Similar curve is also obtained for the discharges in $Ar + H_2$, He, and $He + H_2$.

The plasma length on the downstream direction of the gas flow changes with the length of the pyrex tube, where other paremeters are fixed to a constant value. Therefore we have employed the length on the upstream direction as one half of the real plasma length, which is sketched in **Fig. 5.** It shows a gradual increase and saturation with the input power. At the power of 20 kW, L reaches to about 35 cm in N_2 plasma. While dependence of the plasma diameter on the input power is shown in **Fig. 6.** It has the same tendency with L and becomes about 15 mm at $P_i = 20$ kW.

When the gas flow rate is increased the plasma dimension varies a little. This procedure is given in **Fig. 7.** Plasma diameter decreases with the gas flow but it again increases after the flow rate exceeds 300 l/min. This process is also clarified from photographic method. Reflected power shows a similar curve with the diameter. Meanwhile plasma length hardly decreases on the upstream direction but on the downstream one top of the plasma beam seems to be blown out by the strong gas flow of about 500 l/min. When the flow rate is lowered to 50 l/min, flash over on the corner edge of the cavity resonator begins to occur at this power of 16 kW, as the plasma

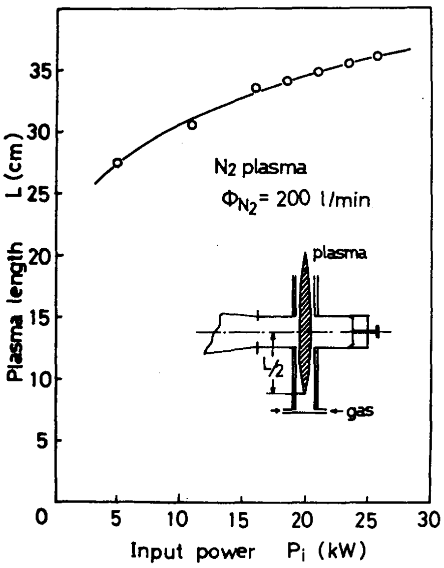

Fig. 5. Change of plasma length measured with photographic method for various input powers. L is determined by the length of the plasma on the upstream side of the gas flow.

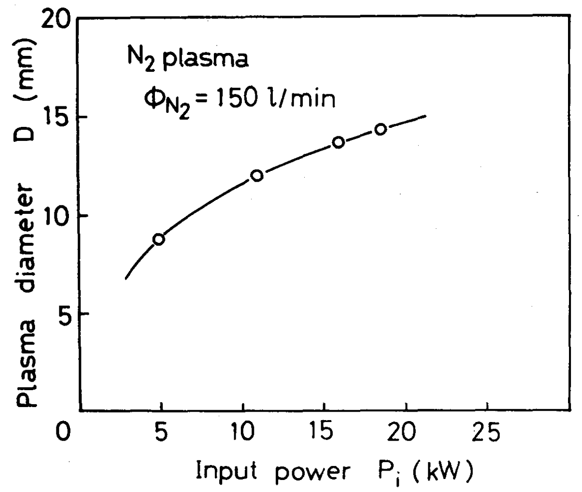

Fig. 6. Dependence of plasma diameter on input power. D is decided from half width of the radial distribution of the light emission of band spectrum head at $\lambda \cong 4700$ Å.

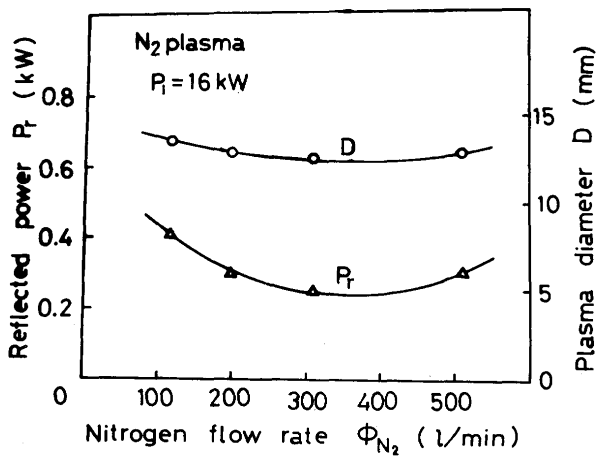

Fig. 7. Change of plasma diameter, D and reflected power, P_r for various nitrogen flow rate, ϕ_{N_2}.

approaches to the wall of the pyrex tube. So that there is a critical flow rate at a given power for the plasma beam to exist stably avoiding this flash over.

In **Fig. 8** typical radial distribution of the light emission ($\lambda \cong 4700$ Å, band head) traced on X-Y recorder is drawn for various powers. As is already stated the plasma diameter is decided from half width of this profile. It should be emphasized that as the input power is increased the peak intensity shifts to the side of the power input and a nonsymetry occurs with the power. This phenomenon is observed much clearly in $He + H_2$ discharge as shown in **Fig. 9.** Intensity of H_β line shifts sharply to the input side and the nonsymetry of the profile becomes stronger and stronger with the power input.

The effect of hydrogen mixing is shown in **Fig. 10.** Plasma diameter and reflection of power decrease

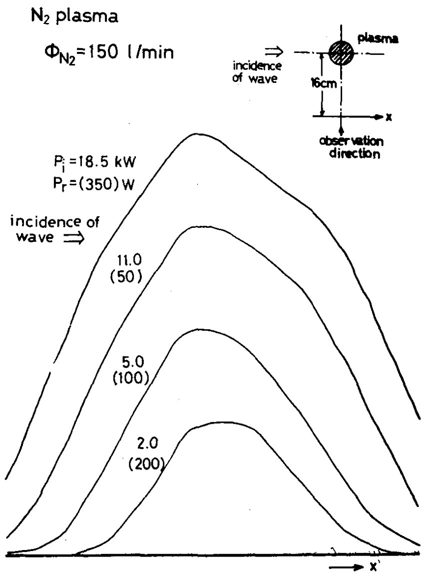

Fig. 8. Trace of radial distribution of band spectrum at $\lambda \cong 4700$ Å on X-Y recoder for various input powers in N_2 plasma. Abel inversion should be performed to obtain a true radial distribution.

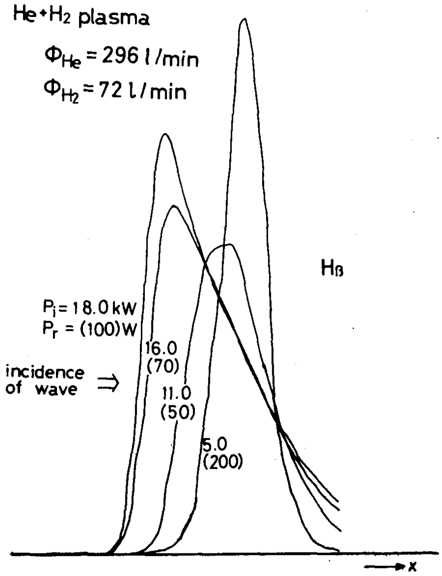

Fig. 9. Trace of radial distribution of of H_β line in $He+H_2$ plasma.

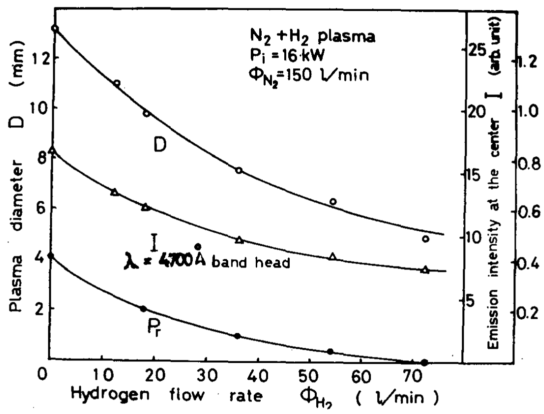

Fig. 10. Dependence of plasma diameter, D and light intensity, I of band head at $\lambda \cong 4700$ Å and reflected power, P_r on the hydrogen flow rate ϕ_{H_2}. Nitrogen flow rate, ϕ_{N_2} is fixed at a value of 150 l/min.

with the increase of hydrogen flow rate. Moreover the emission intensity of $\lambda \cong 4700$ Å band decreases whereas H_β line intensity increases naturally with the hydrogen rate. Mixing of hydrogen causes quenching of band spectra. Similar character is also observed more intensively in Ar or He discharge. **Fig. 11** shows the change of the intensity of HeI line ($\lambda = 5016$ Å) with hydrogen mixing rate in the discharge of He gas. Even a very small hydrogen flow of $\phi_{H_2} = 2.0$ l/min (about 0.5 % to helium) wipes out this line and the further increase brings out the increase only in the intensity of continuum radiation.

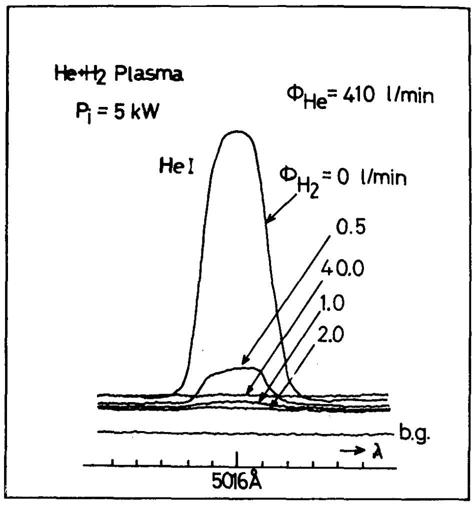

Fig. 11. Recorder trade of change of intensity of HeI line ($\lambda \cong 5016$ Å) in He discharge for a slight mixing of hydrogen. Helium flow rate ϕ_{He} is fixed at a value of 410 l/min.

4. Discussions

The data in Fig. 4 can be interpreted as the result of combination of two effects. When the input power is increased, plasma dimension increases both axially and radially (Figs. 5 & 6). From microwave circuit theory it is well known that a conducting rod inserted into a rectangular waveguide excited with TE_{10} mode shows an equivalent reactance which has a resonance at $l = \lambda/4$, where l is the length of the rod and λ is the wavelength of the wave. At this point all of the input power is reflected towards the source. When $l < \lambda/4$ reactance is capacitive and at $l > \lambda/4$ it is inductive. So that when the plasma length exceeds $\lambda/4$ the coupling between the wave and the plasma is achieved by inductive one and the longer the plasma length the smaller the reflected power should be expected. At $P_i = 2$ kW the plasma length is about 20 cm and already larger than $\lambda/4 = 8.2$ cm. Increase in length results in decrease in reflected power which is obtained at $2 \leq P_i \leq 10$ kW and transformation of TE_{10} mode in a rectangular waveguide to TEM mode in a coaxial waveguide is acomplished due to the plasma beam acting as an inner conductor of a coaxial waveguide. Another factor is the plasma diameter. As we have already stated in the previous report an increase in diameter of the inner conductor of a coaxial waveguide gives also an increase in reflected power, which is equivlent to increase of plasma resistance and reactance. So that as the input power becomes larger the reflection of the wave should be increased. This factor works well in the range of $10 \leq P_i \leq 20$ kW. Both of these two factors are combined as a whole and a minimum value of power reflection should occur at a certain input power ($P_i = 10$ kW).

It should be noted that the radial nonsymetry of the beam (Figs. 8 & 9) will also gives a further increase on the right side of the reflection curve.

A nearly linear dependence of beam diameter and reflected power is also confirmed when other parameters are changed. In Fig. 7 and 10 change of gas flow rate makes a decrease in diameter quite proportionally to that of reflected power. From these results it can be concluded that the plasma beam produced in a rectangular cavity resonator serves as a well matched coaxial transformer of the wave.

Diminishing of intensity of band spectrum in Fig. 10 with hydrogen flow rate seems to offer the cooling of the plasma, but in case of $Ar + H_2$ discharge the increase of hydrogen brings about stronger emission of continuum radiation, needless to say that of H_β line. From the view point of arc discharge it is generally believed that mixing of hydrogen causes thermal pinching of the plasma and a higher temperature is obtained in the arc column. In this experiment the case of $Ar + H_2$ discharge seems to give similar result but in N_2 it is contradictionary. This problem should be discussed in detail after the measurement of plasma temperature is performed for various hydrogen flow rate and will be reported in the next paper.

Shift of the hottest part of the plasma beam to the source side with the increase in power input (Figs. 8 & 9) can be explained by Raizer's Model[4]. When the microwave energy is increased the dissipation of this energy on the surface of the plasma leads to its heating but, as a result of thermal conduction, there is heat transfer from the plasma to the surrounding cold gas. So that further layers are heated, become ionized, and begin to absorb electromagnetic energy. If there is no flow of tangential gas circulation in the pyrex tube this process will cause the propagation of the plasma front to the glass wall and the breaking up of the pipe. Forced convection of gas makes a stable existence of the plasma at a balanced position avoiding cracking of the glass tube. Resultant shift of the peak of light emission and nonsymmetry of the plasma beam take place in this way.

Quenching of neutral line by a slight mixing of hydrogen in He discharge (Fig. 11) is also observed in Ar discharge and this is a strange character of microwave discharge compared with arc or induction plasma. This result is also found in the case of a coaxial type plasmatron in Ref. 1) or in Kapitza's paper, but no investigation of this problem is performed until now. It must be studied theoretically and experimentally from various points of view including thermodynamic nonequilibrium between two gases in a state of mixture.

By lowering the diameter of the pyrex tube from 40 to 30 mm similar stable plasma is obtained up to the maximum oscillator power. In this case the plasma diameter is decreased nearly in proportion to the change in tube diameter. For instance at $P_i =$ 15 kW, plasma diameter, D estimated from photographic method which gives an approximate value gives 21 mm in 40^ϕ tube and 16 mm in 30^ϕ tube with the same gas flow rate of 200 l/min. Too much decrease in tube diameter will result in flash over at the corner edge of the resonator. Experiments by using 20^ϕ or 50^ϕ tube will be performed and the optimum tube dimension must be decided in near future. Furthermore in the present report data of the plasma with ordinary positioning is discussed. But the turning over of the plasmatron, needless to say, makes no difference in the beam configuration. These characters will be confortable to be employed as an actual heat source for various processings.

5. Conclusion

In a reactangular cavity resonator a stable long plasma is produced by tangential flow of N_2 gas up to the maximum microwave input of about 30 kW with a very small reflection of power (below 10 %). Similarly to the result in the previous report plasma volume is enlarged with the power input and at $P_i = 20$ kW plasma diameter reaches to about 15 mm and its length about 35 cm. Dependence of the wave reflection on the input power shows a minimum value at $P_i = 10$ kW. Qualitative interpretation of this character is given: transformation of the incident TE_{10} wave in the rectangular waveguide to TEM wave in the coaxial waveguide with a large dissipation of energy proceeds with the increase in the plasma length, say the increase in the input power, causing a steep decrease in power reflection; also the increase of plasma diameter with the input power results in that of plasma impedance, which is known in microwave circuit theory, causing a rise in the reflected power with the input power. These two factors give rise to the formation of a minimum value in the reflected power. Change of the reflected power with N_2 flow rate or mixing rate of H_2 is also explained correctly with the change in the plasma impedance.

Shift of the radial hottest part of the plasma beam towards the side of the wave incidence and occurrence of radial nonsymmetry of the beam temperature is due to further ionization on the plasma front to the wave which is treated in Raizer's paper.

Diminishing in the intensity of N_2 band spectra and quenching of HeI lines or ArI lines by mixing a small quantity of H_2 are observed. Especially the latter phenomenon is quite remarkable in this microwave discharge compared with arc or induction plasma. Detailed investigation is expected for this problem.

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