High Power Microwave Plasma Beam as a Heat Source (Report III)†
—Energy Absorption Process—

Yoshiaki ARATA*, Shoji MIYAKE**, Akira KOBAYASHI*** and Sadao TAKEUCHI****

Abstract

Measurements of the absorbed power to the plasma and of its temperature for various conditions are performed in a 30 kW microwave plasmatron. The absorbed power reaches to about 80 % of incident one and the plasma temperature in a pyrex tube of 40 mm in diameter is about 6400 K. By decreasing tube diameter to 20 mm it in creases to about 7000 K with a strong decrease in plasma diameter. A week dependence of plasma temperature on input power is obtained, while change of gas flow rate gives no effect on all plasma parameters. Analysis of energy absorption process shows a good agreement between experimental and theoretical results when a virtual cold "wall" is considered to exist by a strong helical flow of the gas, which we call "gas wall".

1. Introduction

Some experimental results on the behaviors of a plasma in a 30 kW microwave plasmatron were given in Report II[1]. It was recognized that the plasma beam played a role of the inner-conductor of a coaxial transformer in rectangular waveguide, with strong absorption of wave energy. Stabilizing effect of the tangential gas flow was also ascertained with a little shift of the hottest part towards the energy source.

This paper gives more detailed analysis of plasma characters and energy absorption process with a comparison between experimental and theoretical results. It is clarified from this analysis that the change of pyrex tube diameter strongly affects the plasma temperature and the helical flow of the gas forms a virtual cold "wall" to the plasma in addition to the stabilizing effect to it on the cylinder axis.

In Sec. 2 experimental methods and results are described including measurements of power absorption and decision of plasma temperature for various conditions. Section 3 gives discussions on the interactions of the microwave and the plasma with a comparison of theoretical and experimental results.

2. Experimental Methods and Results

2.1 Measurement of power absorption

To know the absolute value of the power absorbed to the plasma, calorimetric measurement is performed by using several water-cooling systems, which are sketched schematically in **Fig. 1.** Tangential gas flow (initial temperature T_{gas}) is guided to a cooling duct after the passage of the plasma region and exhausted to the surrounding with final temperature T'_{gas}. While walls of the plasmatron and the guide copper cylinders are heated by the hot gas with a temperature difference ΔT_1, and the wall of the cooling duct is also heated with ΔT_2. Power absorbed to the plasma, P_a is equivalent to the heat that was carried away by the gas and the cooled walls mentioned above.

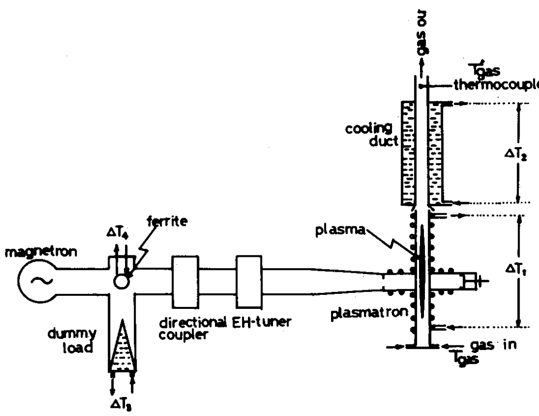

Fig. 1. Schematic diagram of calorimetric power measurement system. The power absorbed to the plasma can be estimated by measuring temperature differences ΔT_1, ΔT_2 of cooling water and also $\Delta T = T'_{gas} - T_{gas}$ of outgoing gas flow.

† Received on July 31, 1974
* Professor
** Research Instructor
*** Graduate Student, Faculty of Fundamental Engineering, Osaka University
**** Graduate Student

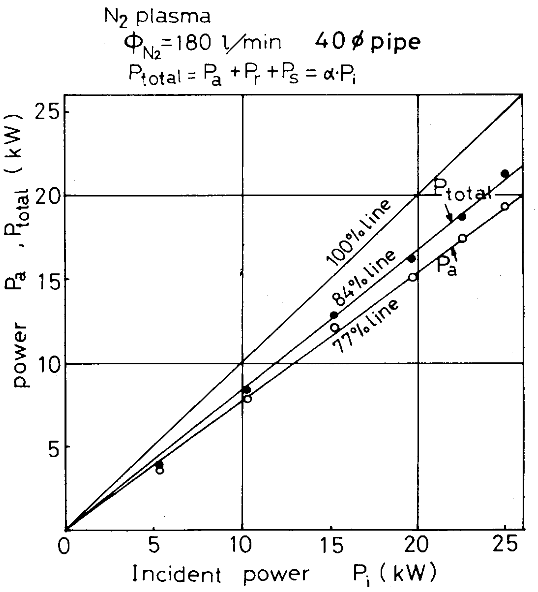

Fig. 2. Dependence of absorbed power P_a to the plasma on incident one P_i. P_{total} is the summation of absorbed power P_a, reflected power P_r and the power to the ferrite part of the circulator P_s. It is all the power we can measure calorimetrically.

Reflected power, P_r from the plasma is measured with a dummy water load in the circulator (temperature difference ΔT_3). Real output power, P_i of the magnetron is calibrated with a water load that can absorb 30 kW microwave energy. Heating at the ferrite part of the circulator, though it is very small, is also evaluated from temperature difference ΔT_4.

In **Fig. 2** the result of calorimetric measurements is plotted for nitrogen plasma with $\phi_{N_2}=180\,l/\text{min}$ in a pyrex tube of 40 mm in diameter. The absorbed power P_a lies on 77 % line for all incident powers P_i. In the figure P_{total} is the sum of P_a, P_r, and the power cpnsumed at the ferrite part of the circulator. P_{total} is all the powers we have measured calorimetrically. This power lies on the line of 84 %. 16 % of incident powers is missing, which will come from losses in other parts (for instance, radiation into the surrounding from the end of the cooling duct, loss at the joint of the waveguide, etc) and from errors in measurements.

2.2 Spectroscopic measurements

From Stark broadening of H_β line plasma density was determined for various conditions by mixing several percentages of H_2 in N_2. Assuming LTE (Local Thermodynamic Equilibrium) plasma temperature is estimated from Saha equation. Measurement of plasma temperature from relative intensity ratio of hydrogen Balmer lines made it possible to compare temperatures obtained with these two methods and a good agreement was satisfied.

Spectroscopic measurements are performed for

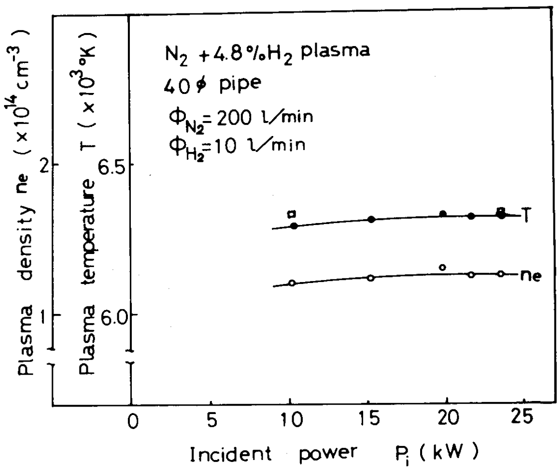

Fig. 3. Plots of plasma temperature T and its density N_e on incident power P_i. The plasma is produced in a pyrex tube of 40 mm in diameter.

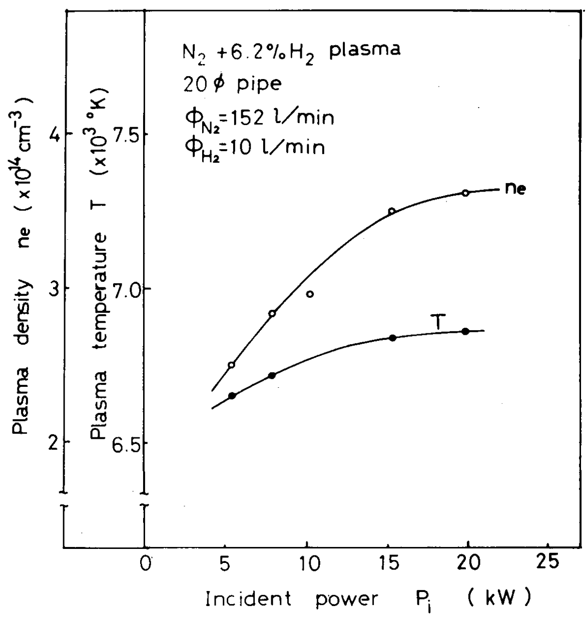

Fig. 4. Dependence of plasma temperature and its density on incident power in case of a pyrex tube of 20 mm in diameter.

various parameters-incident power P_i, nitrogen flow rate ϕ_{N_2}, hydrogen flow rate ϕ_{H_2} and pyrex tube diameter D_t. **Fig. 3** shows a dependence of plasma temperature, T and its density, n_e, on P_i for a tube of $D_t=40$ mm. T is about 6400 K and $n_e=1.0\times 10^{14}\,\text{cm}^{-3}$ and there is little dependence of T and n_e on P_i. Rectangular plots are the data obtained from relative intensity ratio of Balmer lines. They show good agreement with the ones obtained from Saha eq.. By decreasing tube diameter, D_t to 20 mm T increases strongly and the power dependence becomes clearer as is shown in **Fig. 4.** This tendency is plotted in **Fig. 5** for various tube diameters. Indeed plasma diameter, D increases in proportion to D_t and contribution of D_t to the change of plasma temperature is stronger than that of P_i. If we produce a

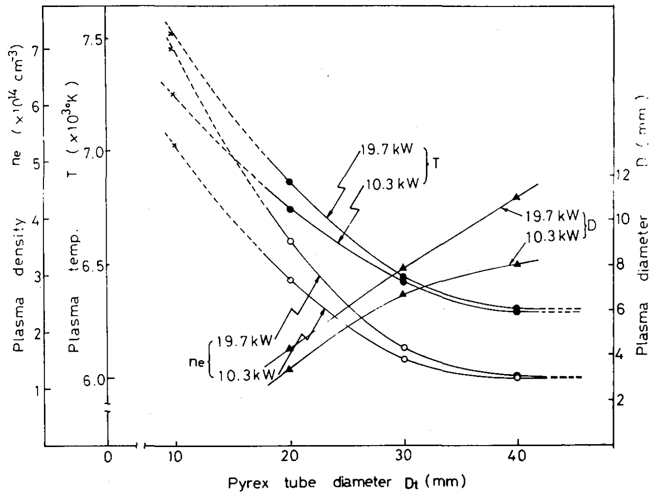

Fig. 5. Change of plasma temperature T and its density n_e and also its diameter D on pyrex tube diameter D_t for two incident powers. The discharge is ignited in nitrogen flow with a mixture of 5 % hydrogen.

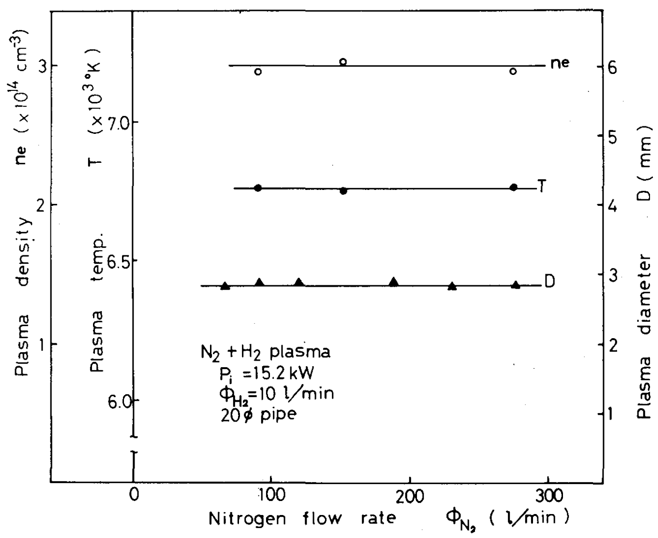

Fig. 7. Relations between plasma parameters and nitrogen flow rate for an input power of 15 kW in a pyrex tube of 20 mm in diameter.

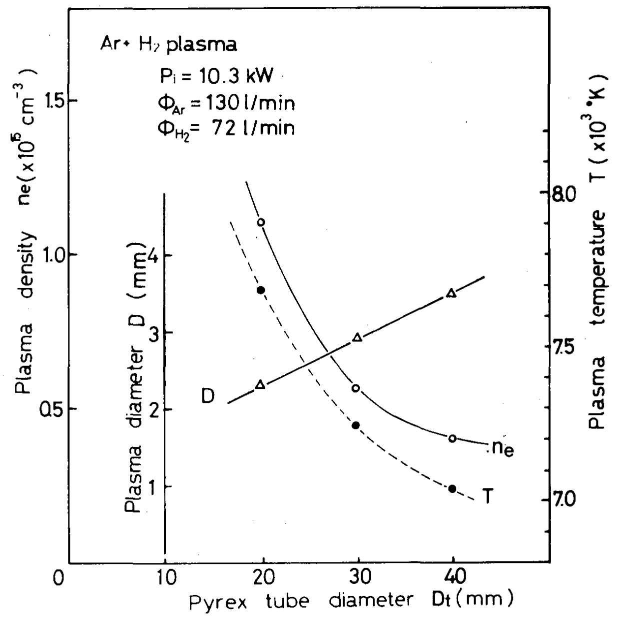

Fig. 6. Dependence of plasma temperature, density and its diameter for various tube diameters in a plasma of a gas mixture of Ar+36 %H_2.

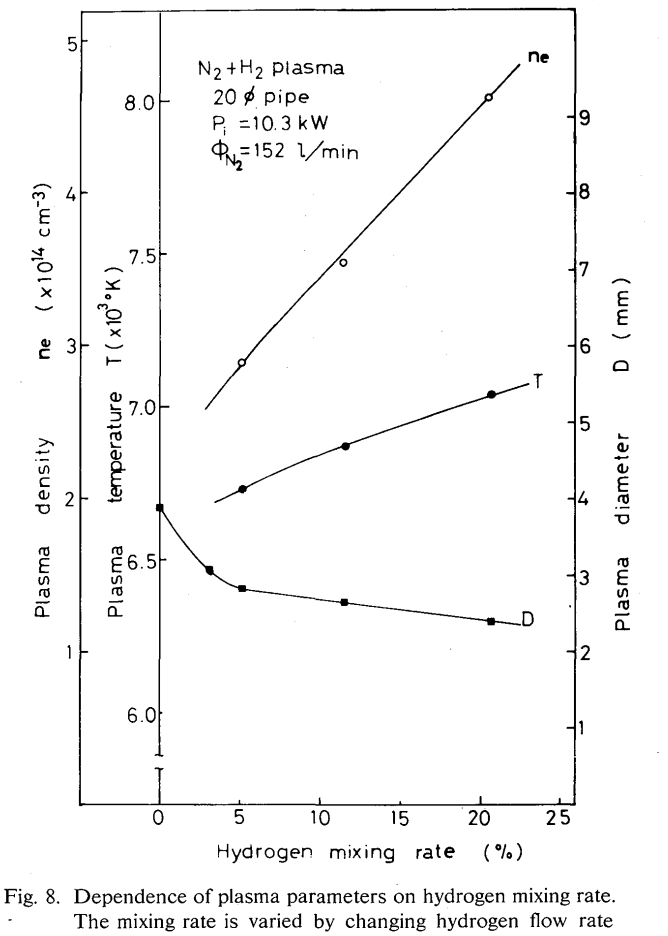

Fig. 8. Dependence of plasma parameters on hydrogen mixing rate. The mixing rate is varied by changing hydrogen flow rate with a constant flow of nitrogen.

plasma in a tube of 10 mm the plasma temperature will reach to 7500 K. Of course similar behavior is also observed in a plasma in a gas mixture of $Ar+H_2$, which is given in **Fig. 6.**

It is shown in **Fig. 7** that change of gas flow rate makes no difference in plasma parameters. By changing N_2 flow rate ϕ_{N_2} from 80 to 300 l/min plasma temperature, its density and also the diameter keep a constant value. Meanwhile the increase in hydrogen mixing rate gives an appreciable increase in plasma temperature as is clearly seen in **Fig. 8.**

3. Discussions

In the theory of high-frequency gas dischange at atmospheric pressure, Yu. P. Raizer in USSR has a good contribution in various frequency ranges (RF[2], UHF[3] or optical frequency[4]) and his review article of this problem is given in ref. 5. In case of UHF discharge[3] he gives a peculiarity in the fact that $\upsilon_{eff}/\omega \approx 1$ is satisfied, where υ_{eff} is the effective collision frequency of electrons with neutral atoms and ω is the wave frequency. While in case of RF discharge, $\upsilon_{eff}/\omega \gg 1$ and at optical frequency $\upsilon_{eff}/\omega \ll 1$ are generally fulfilled. His analysis can essentially be adopted to our case but it is rather crude in the fact that in his model the wave enters a semi-infinite plasma and the effect of finite dimension of the plasma is considered only approximately. In the plasma we have produced $\upsilon_{eff}/\omega \gg 1$ is generally obtained since the wave frequency is not so large but the finite dimension of the plasma, namely, the fact that the plasma diameter is of the same order with the skin depth and changes widely depending on external parameters makes it impossible to apply Raizer's model to the plasma under present investigation.

B. E. Meierovich independently has studied the theory of an equilibrium microwave gas discharge in a cylindrical cavity or a waveguide.[6)~8)] An individuality of his analysis is that he has treated the problem without imposing any restrictions on the penetration depth of the field in the normal skin effect. The structure of the discharge is studied and equations are obtained which determine the dependence of the discharge paremeters on the input power. This enables us to take into account the comparativeness of plasma diameter and skin depth, and also the effect of pyrex tube diameter in the definition of plasma temperature at a given input power.

Consider an infinitely long cylindrical stationary plasma in LTE, in which the Joule heat is released by microwave field from radial direction and is transmitted by heat conduction to the cold wall of radius R. The conduction of the gas and the radiation are neglected and the electric field vector is assumed to be parallel to the cylinder axis, while the non-vanishing component of the magnetic vector is H_ϕ. Moreover the process is confined to the region of relatively low temperatures where ionization-equilibrium formula can be applied.

Combining Maxwell's and energy balance equations a system of equation is obtained which determines the maximum temperature, T_m in the plasma and the parameter, α of the skin effect as functions of the power input per unit length P_0.

$$P_0 = 4\pi\upsilon(\alpha)\kappa_m T_m^2/V_i,$$
$$\alpha\varsigma(\alpha) = (R/\delta_m)\exp(-2\pi\int_{T_0}^{T_m}\kappa dT/P_0), \qquad (1)$$

where κ-thermal conductivity of the gas, V_i-ionization potential, δ-skin depth, T_0-temperature of the cold wall. The suffix m denotes the value of a quantity at $T=T_m$. Dependences of $\upsilon(\alpha)$ and $\varsigma(\alpha)$ on α are numerically calculated and are given in Fig. 2 of ref. 7.

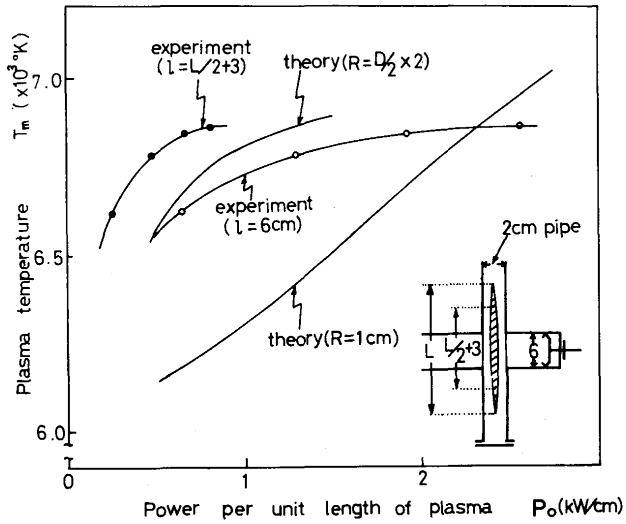

Fig. 9. Relation between maximum plasma temperature and incident power per unit length P_0. Two experimental curves are brought from Fig. 4. Theoretical curves are drawn by using eq. (1).

Fig. 9 shows the comparison of theretical and experimental relation between T_m and P_0 for the plasma in a pyrex tube of 20 mm in diameter. By setting R=1 cm a theoretical curve is drawn. While it is experimentally observed that the plasma radius increases with the power input P_0 (see Report II) and the region where there is no light emission is at twice that of the plasma radius. If we consider that the cold wall, at which heat flow from the plasma vanishes, is equivalent to this region ($R=(D/2)\times 2=D$), another theoretical curve can be obtained as is also given in the figure.

Two experimental curves are brought from the data in Fig. 4. As for the definition of P_0, $P_0=P_a/l$ is taken where P_a is the power measured calorimetrically (Fig. 2) and l is the length where the wave is absorbed. If l is considered to be the height of the waveguide, $l=6$ cm is chosen and if l is given as a half-length of the plasma itself, $l=(L/2)+3$ is taken as sketched in the figure.

Good agreement between theoretical and experimental curves is obtained by setting R=D and not by $R=D_t/2=1$ cm. This means that a virtual cold "wall" may exist between the pyrex tube and the plasma due to the strong helical flow of the gas. At this "wall" the heat flow is considered negligibly small, after which we name "gas wall". Its diameter is denoted by D_g.

A question is unanswered as to the selection of l.

If we consider $l=6$ cm should be the value, further experiment must be undertaken changing the height of the waveguide.

In the comparison mentioned above the effect of the gas conduction on to the energy balance is neglected theoretically, though a rather strong flow of the gas is guided during experiment. Experimental result in Fig. 7 answers for this disregard, since it is clear that none of plasma parameters are affected by the change of gas flow rate. Indeed we may say that the helical gas flows only along on the peripheny of the plasma, stabilizing it on the axis and forming a "gas wall" to the plasma.

Results in Figs. 5 and 6 can also be explained from eq. (1). By decreasing tube diameter D_t the plasma diameter D decreases, so that the smaller the tube diameter, the smaller the effective "wall" diameter D_g is ascertained. This brings about the reduction of α and $\upsilon(\alpha)$ in eq. (1), which in turn offers an increase in T_m at a given value of P_0. This result is similar to the one in a constricted arc discharge and may be interpreted as the effect of thermal pinching.

Table 1.

	T (°K)	$\sigma_{\odot}$ (cm^2)	σ (mho/cm)	κ (W/m·deg)
N_2	6×10^3	1.0×10^{-15}	4.0×10^{-2}	2.0×10^0
	7×10^3	1.0×10^{-15}	4.0×10^{-1}	4.5×10^0
H_2	6×10^3	1.5×10^{-15}	1.0×10^0	2.0×10^0
	7×10^3	1.5×10^{-15}	3.0×10^0	2.5×10^0

T : Plasma temperature

$\sigma_{\odot}$: Collision cross section

σ: Electrical conductivity

κ: Thermal conductivity

Fig. 8 indicates that by increasing the flow rate of hydrogen at a constant value of nitrogen flow rate, the plasma diameter decreases together with the increase in temperature. Similar behavior is also observed in an usual arc plasma. Let's consider this phenomenon in detail.

Some physical constants-electron-neutral collision cross section, $\sigma_{\odot}$, electrical conductivity σ and thermal conductivity, κ for nitrogen and hydrogen are tabulated in **Table 1**[9),10)] for a plasma at temperatures $6\sim7\times10^3$ K. The values of $\sigma_{\odot}$ and κ are similar for both N_2 and H_2 but σ is one order of magnitude larger in H_2 than in N_2. These features suggest that LTE between N_2 and H_2 can easily be established in those temperatures and electrical conductivity of the plasma will abruptly be increased by mixing a bit of hydrogen, causing a further heating of it. Meanwhile near the boundary region where the plasma temperature is lower than 5×10^3 K, thermal conductivity of H_2 is so large that the cooling effect by hydrogen on the periphery brings out the decrease in plasma diameter. These two factors will cause effective thermal pinching in the mixture of H_2 in N_2. In an arc plasma whose temperature is usually around or larger than 1×10^4 K, σ of N_2 is comparable with that of H_2. Effect of pinching in this case will mainly be caused by cooling action on the plasma surface.

In Report II it is pointed out that there appears a minimum of power reflection on increasing its input. It must be revised, however, since an error was introduced in the measurement due to mismatching of EH tuner. It was experimentally clarified that at a power input larger than 5 kW the reflection could always be zero. The inductive coupling of the wave to the plasma beam has already been accomplished at 5 kW, since the plasma was longer than a quarter of the wavelength. Change of capacitance or inductance of the plasma by further increase in power input can be matched again with EH tuner keeping no reflection of power.

4. Conclusion

In a microwave plasmatron of rectangular waveguide type it is experimentally decided that the absorbed power to the plasma reaches to about 80 % of incident one and the plasma temperature in a tangential flow of nitrogen is about 6400 K with a little dependence on input power. By decreasing pyrex tube diameter from 40 to 20 mm it increases to about 7000 K acompanying a sharp decrease in plasma diameter.

Change of gas flow rate essentially gives no influence on all plasma parameters-temperature, density and diameter, and a contribution of the circulating flow to the formation of virtual cold "gas wall" is assumed in addition to the stabilizing effect.

Analyzing energy absorption process with a model of B. E. Meierovich, a comparison of experimental and theoretical results of the relation between plasma temperature and input power is performed, and a good agreement is obtained when the "gas wall" is considered between the pyrex tube and the plasma, whose diameter is to be around twice that of plasma.

Effect of hydrogen mixing on plasma parameters is experimentally investigated. A further heating at the plasma by a larger electrical conductivity of H_2 than of N_2 and a stronger cooling on the surface by its larger thermal conductivity are clarified in the region of temperature under experiment.

References

1) Y. Arata, S. Miyake, S. Takeuchi and A. Kobayashi: "High Power Microwave Plasma Beam as a Heat Source (Report II) —Characteristics of 30 KW Plasmatron—", JWRI **3**, No. 1, 21 (1973).
2) Yu. P. Raizer: "High-Frequency High-Pressure Induction Discharge and the Electrodeless Plasmatron", Sov. Phys.-USPEKHI **12**, No. 6, 777 (1970).
3) Yu. P. Raizer: "Propagation of a High-Pressure Microwave Discharge", Sov. Phys.-JETP **34**, No. 1, 114 (1972).
4) Yu. P. Raizer: "The Feasibility of an Optical Plasmatron and its Power Requirements", JETP Lett. **11**, No. 3, 120 (1970): "Subsonic Propagation of a Light peak and Threshold Conditions for the Maintenance of Plasma by Radiation", Sov. Phys.-JETP **31**, No. 6, 1148 (1970).
5) Yu. P. Raizer: "Propagation of Discharges and Maintenance of a Dense Plasma by Electromagnetic Fields", Sov. Phys.-USPEKHI **15**, No. 6, 688 (1973).
6) B. E. Meierovich, "On the Structure of the Transition Layers in a High-Frequency Gas Discharge", Sov. Phys.-JETP **34**, No. 1, 121 (1972).
7) B. E. Meierovich: "Contribution to the Theory of an Equilibrium High-Frequency Gas Discharge", Sov. Phys.-JETP **34**, No. 5, 1006 (1972).
8) B. E. Meierovich: "Diffusion in a High-Frequency Gas Discharge", Sov. Phys.-JETP **36**, No. 2, 291 (1973).
9) A. G. Engelhardt, A. V. Phelps and C. G. Risk, "Determination of Momentum Transfer and Inelastic Collision Cross Sections for Electrons in Nitrogen Using Transport Coefficients", Phys. Rev. **135**, No. 6A, A1566 (1964).
10) P. P. Kulik: "Coll. Essays on Physics and Chemistry of Low Temperature Plasma", L. S. Polak, Ed., p. 39 (Nauka, 1971) (in Russian).