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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 plasmator. 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 increases 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 plasmator were given in Report II††. 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 plasmator and the guide copper cylinders are heated by the hot gas with a temperature difference $\Delta T_1$, and the wall of the cooling duct is also heated with $\Delta T_2$. 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 $\Delta T_1$, $\Delta T_2$ of cooling water and also $\Delta T = T_{gas} - T_{gas}$ of outgoing gas flow.

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Reflected power, $P_r$, from the plasma is measured with a dummy water load in the circulator (temperature difference $\Delta T_j$). 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 $\Delta T_j$.

In Fig. 2 the result of calorimetric measurements is plotted for nitrogen plasma with $\phi_{N_2}=180$ L/min in a pyrex tube of 40 mm in diameter. The absorbed power $P_a$ lies on 77% for all incident powers $P_i$. In the figure $P_{\text{total}}$ is the sum of $P_a$, $P_r$, and the power consumed at the ferrite part of the circulator. $P_{\text{total}}$ 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$_2$ 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 various parameters: incident power $P_i$, nitrogen flow rate $\phi_{N_2}$, hydrogen flow rate $\phi_{H_2}$, 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 $n_e=1.0\times10^{14}$ 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, $D_t$ increases in proportion to $D$, and contribution of $D_t$ to the change of plasma temperature is stronger than that of $P_i$. If we produce a
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+H₂, 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 N₂ flow rate \( \Phi_{N_2} \) 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 discharge at atmospheric pressure, Yu. P. Raizer in USSR has
a good contribution in various frequency ranges (RF\textsuperscript{20}, UHF\textsuperscript{20} or optical frequency\textsuperscript{10}) and his review article of this problem is given in ref. 5. In case of UHF discharge\textsuperscript{20} he gives a peculiarity in the fact that $u_{\text{eff}}/\omega \approx 1$ is satisfied, where $u_{\text{eff}}$ is the effective collision frequency of electrons with neutral atoms and $\omega$ is the wave frequency. While in case of RF discharge, $u_{\text{eff}}/\omega \gg 1$ and at optical frequency $u_{\text{eff}}/\omega \ll 1$ 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 $u_{\text{eff}}/\omega \gg 1$ 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.\textsuperscript{60-63} 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 parameters 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 $H_\phi$. 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, $\alpha$ of the skin effect as functions of the power input per unit length $P_\phi$.

$$P_\phi = 4 \pi u(\alpha) k_\alpha T_m^{2}/V_1,$$

$$\alpha \equiv (R/\delta_\alpha) \exp(-2\pi \int_0^{\delta_\alpha} \kappa dT/P_\phi).$$

where $\kappa$-thermal conductivity of the gas, $V_1$-ionization potential, $\delta$-skin depth, $T_m$-temperature of the cold wall. The suffix $m$ denotes the value of a quantity at $T=T_m$. Dependences of $\nu(\alpha)$ and $\psi(\alpha)$ on $\alpha$ are numerically calculated and are given in Fig. 2 of ref. 7.

Fig. 9 shows the comparison of theoretical and experimental relation between $T_m$ and $P_\phi$ 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 $P_\phi$ (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 $P_\phi$, $P_\phi = P_\phi/l$ is taken where $P_\phi$ 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 $R=D/2=1$ 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 $D_y$.

A question is unanswered as to the selection of $l$. 

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\textsuperscript{14} Trans. J. WRI Vol. 3, No. 2 1974
If we consider \( l = 6 \text{ cm} \) 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 periphery 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 \( D_1 \), the plasma diameter \( D \) decreases, so that the smaller the tube diameter, the smaller the effective “wall” diameter \( D_x \) is ascertained. This brings about the reduction of \( \alpha \) and \( v(\alpha) \) 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.

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<tr>
<th>( T ) (°K)</th>
<th>( \sigma_e ) ((\text{cm}^2))</th>
<th>( \sigma ) ((\text{mho/cm}))</th>
<th>( K ) ((\text{W/m.deg}))</th>
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<td>( 6 \times 10^3 )</td>
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<tr>
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- \( T \): Plasma temperature
- \( \sigma_e \): Collision cross section
- \( \sigma \): Electrical conductivity
- \( K \): Thermal conductivity

Table 1: Parameters for \( N_2 \) and \( H_2 \)

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, \( \sigma_{eo} \), electrical conductivity \( \sigma \) and thermal conductivity, \( k \) for nitrogen and hydrogen are tabulated in Table 1 for a plasma at temperatures \( 6 \sim 7 \times 10^3 \) K. The values of \( \sigma_{eo} \) and \( k \) are similar for both \( N_2 \) and \( H_2 \) but \( \sigma \) 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 \( 5 \times 10^3 \) 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 \( 1 \times 10^4 \) K, \( \sigma \) 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 plasmotron 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 accompanying 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


