GENERATION OF LARGE AREA THERMAL PLASMA BY INDUCTION HEATING WITH 50-KHZ FREQUENCY HIGH POWER SOURCE

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Abstract Numerical and experimental approach was made to produce a large area induction thermal plasma for high rate, uniform processing. The transient is initiated in a small dc plasma as a source by superimposing 50-kHz magnetic field to it The time necessary to reach a new steady state plasma with a larger diameter of 100 mm was found to be 90 ms and the minimum sustaining power for the plasma was estimated to be 140 kW under the plasma pressure of 760 torr. Experiments were performed to produce the wide area plasma under a soft vacuum condition of 60 torr. At a power level of 70 kW, the 50- kHz field coupled with a source plasma and expanded it successfully to a wide plasma of 100 mm in diameter. The temperature of the induction plasma was estimated around 10,000 K.

1 Introduction

The inductively-coupled radio frequency thermal plasma produced in a high pressure gases with a power of the order of hundred kW, is now gradually becoming an important source with high-temperature and high- reactivity, either for processing of new functional materials or destruction of circumstance depleting substances[1]. Although the volume of the plasma has been restricted to around 50 mm in diameter from the short skin depth of the applied frequency of the order of MHz, a plasma with a large area is required for a higher rate of processing as a future technology.

An attempt to expand the high temperature plasma field was made in this paper by superimposing a low-frequency(50kHz) magnetic field on a small source plasma being produced with d.c. mode. Because the penetration depth of such a low frequency field is as long as few hundreds mm, a more wider plasma in diameter is expected to be produced. As a first step, a numerical approach was made for simulate the dynamic behavior of a source plasma initially having a small diameter of 30 mm after step-like impose of 50-kHz electro-magnetic fields, was made based on time-dependent balance equations developed for the purpose. The converging time necessary for reaching a steady state with a diameter of 100 mm was investigated for various magnetic field strengths. The minimum field strength necessary to motivate the plasma expansion and the corresponding minimum power necessary to sustain the large area plasma in stable mode were both estimated. Experiments were carried out by using 50-kHz oscillator with a maximum power of 300 KVA under several power and pressure conditions. The temperature distribution of the produced induction plasma was measured by spectroscopic method.

2 Basic Equations

The energy conservation and the mass conservation equations for the induction thermal plasma can be written, in one-dimensional model(radial direction) as equation (1) and (2)[2]. The radial diffusion velocity v_r is derived from the mass conservation equation (2). The Maxwell's equations for the electrical and magnetic fields penetrating the plasma were simultaneously solved to estimate the joule heating term appears in eq.(1) at each time instance.

The boundary conditions in the calculation are essentially same as those of the previous works in steady states[3,4]. The procedure of deriving the discretization equation from the differential equation is based on the 'control volume' method proposed by Patankar[5].

$$\begin{aligned} \rho C_P \frac{\delta T}{\delta t} + \rho C_P v_r \frac{\delta T}{\delta r} &= \frac{1}{r}\frac{\delta}{\delta r}(r\kappa \frac{\delta T}{\delta t}) + \sigma E^2 \\ & W_{D.C.} - W_{rad} - W_{conv} \end{aligned} \tag{1}$$

$$\frac{\delta \rho}{\delta t} + \frac{1}{r}\frac{\delta}{\delta r}(r\rho v_r) = 0 \tag{2}$$

The transport and thermodynamic properties of Ar gas necessary for the computation are taken from the data in the previous works [6][7][8]. Calculations were made for pure Ar plasma with a pressure of 0.1 MPa(760 torr).

The calculation procedure of expanding behavior of a source plasma by superimposing the 50-kHz magnetic field is as follows. As an initial steady state, a small-area plasma with an effective radius of 30 mm is assumed. The electrical conductivity of the plasma is high enough to couple with the oscillating magnetic field and absorb the joule heating energy. At the time t=0, 50-kHz magnetic field with a certain strength is applied as a step-like function, then the transient takes place in the small source plasma because the input power from the low frequency field exceeds the output power from the plasma. The time step dt is taken as 0.2 ms through the entire calculation. The definition of the convergence of the calculation was made when the temperature variation dT between each time step becomes less than 0.05 K at all the grid point. The temperature distribution of the small source plasma as an initial condition was cited from reference [9]. The axial length of the plasma was kept through the calculation to 7 cm.

3 Results of Calculation

3.1 Plasma expansion by applying 50-kHz field

Fig.1(a) and 2(a) show the expanding process of the initial temperature distribution of the small source plasma with a diameter of 30 mm after a step-like superimposition of 50-kHz magnetic field with a strength of 400 AT/cm, at the pressure of 760 and 76 torr, respectively. The axis temperature was initially kept at around 12,000 K before t=0 with a d.c. plasma power of 0.5 kW/cm. It can be noticed that the high temperature zone expands slowly toward the outer portion after t=0, according to the relatively weak coupling of the applied 50-kHz magnetic field with the conducting area of the plasma. Such a slow transient continues until t=60 ms.

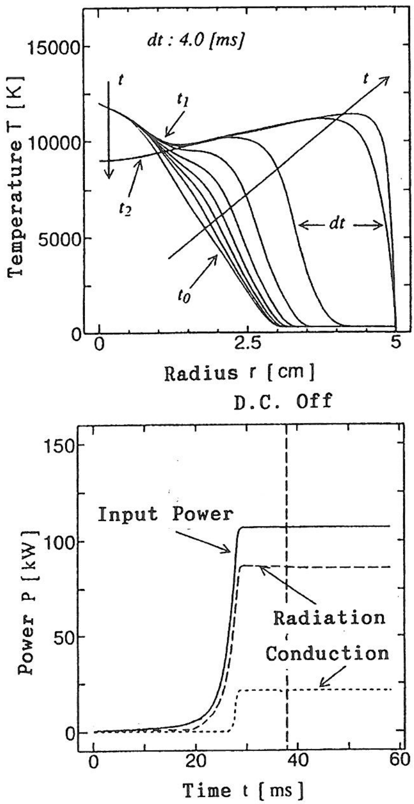

Fig.1 Transient after superimposition of 50-kHz field (P=760 torr)

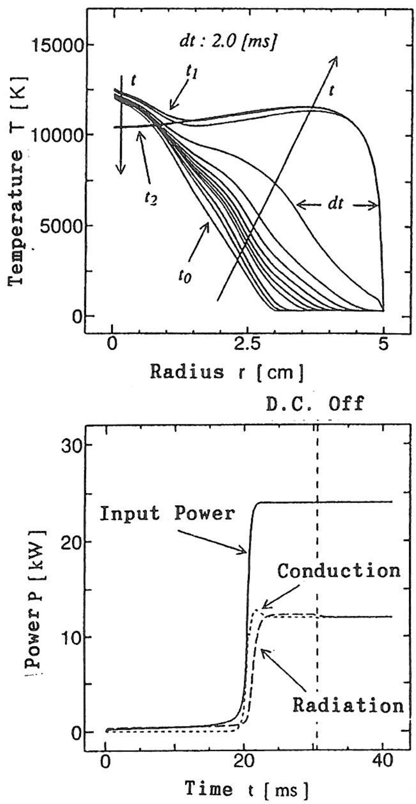

Fig.2 Transient after superimposition of 50-kHz field (P=760 torr)

After this time point, a quick expansion of the plasma occurs toward the restricting wall (r=50 mm) reflecting the fact that the growing plasma with relatively larger diameter absorbs effectively the joule energy from the applied 50-kHz field. And at around t=90 ms, the plasma finally reaches a new steady state where a flat temperature profile with a wider radius of 50 mm. The temperature at the outer portion reaches a value of around 12,000K and it decreases gradually toward the axis direction. This is an inherent feature of the inductively coupled plasma and comes from the fact that the joule heating for sustaining the high temperature plasma takes place at the outer portion according to the skin effect of the applied electro-magnetic field. Another short time transient can be observed in these figures from t=t1 to t2, where the d.c. power used to establish the initial source plasma was cut immediately after the first conversion(t=t1). Even after the source plasma is diminished the radial wide plasma is sustained steadily by absorbing the necessary energy from the existing 50-kHz field through inductively coupled effect.

Fig.1(b) shows the time-dependent characteristics of each of the plasma power after the step-like impose of the 50-kHz field at 760 torr pressure. From the time instance of t=20 ms, the joule input power increases sharply from almost zero to 100 kW and this causes the plasma to increase in the volume fast toward the outer direction. Accompanying with this increase of the input power, the thermal conduction loss as an important part of the output from the plasma also increases sharply mainly because of the increase of the gradient of the temperature at the plasma edge. Another output power from the plasma appears as the radiation loss. This is brought about by the emission from the high temperature zone of above 10,000 K which is gradually enlarged with the time. These losses finally balance with the input joule power at around t=30 ms, where a new steady state achieves. In Fig.3(b) for lower pressure case of 76 torr, a relatively faster response time is observed compared to 760 torr case. The joule input starts to increase at around 6 ms and the time necessary for reaching a new state is as short as 10 ms, reflecting the fact that the mass of the plasma to be transported radially is small under low pressure condition.

3.2 Response time and minimum sustaining power

The response time of the plasma necessary to reach a new steady state after superimposing the 50-kHz field was found as 30 ms for the magnetic field of 400 AT/cm at 760 torr pressure. It should be mentioned, however, that the response time of the plasma is affected strongly by the strength of the applied electro-magnetic field. Especially, the considerable long time spent in the early stage of expansion from t=0 to 20 ms in Fig.2, is reflected by the fact that a very weak interaction between high temperature zone and the applied field takes place. This means that the power being absorbed is too small to motivate the plasma to expand in its volume toward the radial direction. Fig 4. shows the dependence of the converging time of the plasma upon the strength of the applied magnetic field, H[AT/cm] at the pressure of 760 torr. The relations between the H[AT/cm] and the total power[kW] for 7-cm length plasma are also represented. It can be observed clearly that the response time t1 becomes shorter when the field strength H is increased. Typical value of t1 is 150 and 30 ms for H=300 and 400 AT/cm, respectively. The figure also indicates that the response time reaches gradually a constant value with the increase of the field strength H. This can be read as around 20 ms in this case.

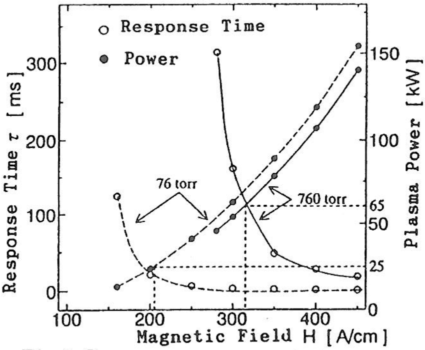

Fig.3 Converging time and plasma power as a function of magnetic field strength H

A special attention should be paid to the profile of the curve in Fig.3, that is, a sharp increase of the converging time is found at the weak strength side less than H=300 AT/cm. This implies that when the applied field strength H is less than this value, the response time t1 becomes infinite. This means in turn that the plasma take no reaction against the application of the 50-kHz electro-magnetic field. This gives us a concept of minimum sustaining field Hmin or minimum sustaining power Pmin for a plasma to expand and reach finally a plasma with a wide area. These are found from the figure to be Hmin = 300 AT/cm and Pmin = 60 kW for the case of 50-mm plasma radius. The same estimation was made for lower pressure case of 760 torr and Hmin and Pmin were found as 200 AT/cm and 25 kW, respectively.

4 Generation of Large Area Induction Plasma

Fig.4 shows a schematic diagram of the experimental set-up which includes an induction plasma torch newly designed, a vacuum chamber, a d.c. power supply and a 50-kHz oscillator. The rated power of the oscillator is 350 kW. A 7-turn induction coil has a diameter of 130 mm and a height of 70 mm and inside it a quarz tube with an inner diameter 100 mm is installed. At the upper portion of the induction plasma, a d.c. plasma torch is mounted to generated a small source plasma as an initial condition. The whole system is first depressurized down to several torr condition, then a source d.c. plasma is generated. The 50 kHz magnetic field is next applied to this source

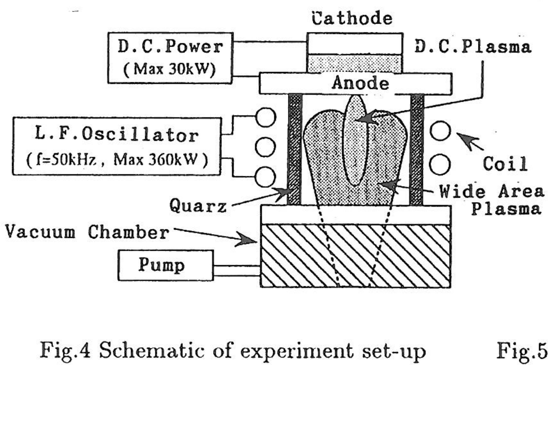

Fig.4 Schematic of experiment set-up

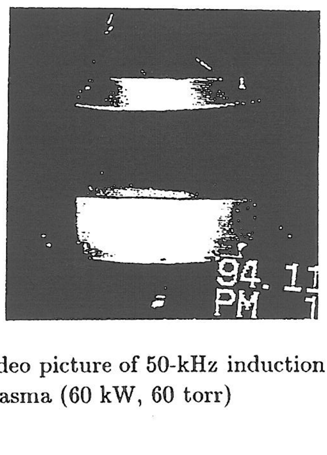

Fig.5 Video picture of 50-kHz induction plasma (60 kW, 60 torr)

plasma and the expanding process of the plasma was observed and analyzed by video camera and spectroscopic measurement.

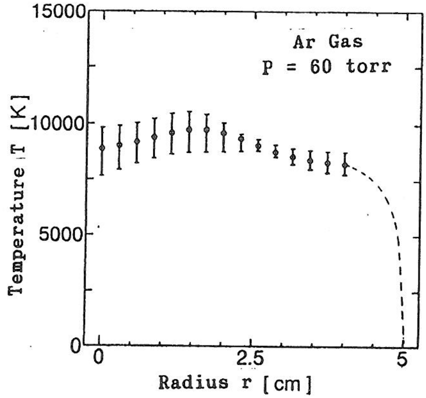

Fig.6 Measured temperature distribution

Fig.5 shows a video picture of successful operations of producing large area induction plasma at 60 torr pressure condition. The d.c. power to establish a small source plasma is 1.5 kW, while the superimposed power of low frequency oscillator is 60 kW in this case. The corresponding temperature distribution inside the plasma is shown in Fig.6, which is derived from 'Boltzmann plot' of Ar I spectral lines detected by multi-channel optical system. An uniform distribution of the temperature can be achieved across the wide diameter with taking a value of 10,000 K.

5 Conclusion

Time-dependent conservation equations were solved numerically for analyzing the radial expanding process of the induction thermal plasma, after superimposing the low frequency of 50-kHz magnetic field to a small area source plasma. The time necessary to reach a new steady state plasma with a large diameter of 100 mm was found to be around 10 to 30 ms at a pressure range of 76 to 760 torr. The dynamic model proposed here also gives a concept about the minimum sustaining power, which was estimated for 100-mm diameter, 70-mm length plasma to be 20 and 60 kW at the plasma pressure of 76 and 760 torr, respectively. The experiment carried out at lower soft vacuum condition of 60 torr showed that the expansion of small area source plasma can be realized by using 50-kHz oscillator at a power level of 60 kW and a wide area plasma can be produced with a flat profile of temperature around 10,000 K.

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