# NUMERICAL AND EXPERIMENTAL ANALYSIS OF FREQUENCY EFFECT ON INDUCTIVELY COUPLED THERMAL PLASMAS

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**ABSTRACT:** The investigation of frequency effect on RF thermal plasmas has been carried out with comparing the theoretical and experimental results. An Ar-$H_2$ atmospheric pressure plasma is successfully operated at 0.5 MHz frequency and up to 75 kW RF power condition. Lower induction frequency generates longer and narrower plasma region. The experimental tendencies indicate good agreement with the results of the calculated isotherms.

## I. INTRODUCTION

Radio-frequency (RF) induction thermal plasmas have a number of applications with chemical reactions: synthesis of ultrafine powders, plasma spraying, waste treatment and so on. The applied frequency is strongly related to the size of the plasma torch and also to the distributions of the temperature, velocity and species concentration. A theoretical investigation of the frequency effect on local thermodynamic equilibrium (LTE) conditions was performed by Mostagimi and Boulos[1]. Their computations were carried out for argon plasmas over the frequency ranging from 3 to 40 MHz. They showed that higher frequency results in lower temperature, and the difference between the electron and the atom/ion temperatures is increased. The effect of frequency on the dynamic behavior of RF plasmas was calculated by Sakuta *et al.*[2]. They showed that a frequency of a few hundred hertz is the lower limit applicable. They also succeeded to ignite 50kHz low pressure plasma[3].

In a previous paper[4], we have performed numerical simulations of the frequency effect on characteristics of RF argon-hydrogen plasmas. The induction frequency has strong effect on the skin depth resulting in the off-axis peak distribution of the temperature.

The purpose of the present work is to investigate the characteristics in argon-hydrogen plasmas generated at lower frequency with comparing the results of the numerical simulations with the experimental data. The induction frequency is important in determining the plasma torch size, since lower frequency results in an increase in the torch size from the theory of induction heating.

## II. NUMERICAL FORMULATION

A model of RF plasma torch is given in Fig. 1, and the operating conditions are summarized in Table 1. The coil consists of 2 turns and applies the induction frequency from 0.5 MHz to 4 MHz to the plasma to investigate its effect on the plasma characteristics. The actual RF power level at the plasma torch is 60 kW. The model is concerned with a water-cooled steel injection tube along the torch axis. The sheath gas injected with swirl from outer slots protecting the inner surface of the quartz tube is the mixture of argon and hydrogen.

The calculations are based on the following assumptions; (a) steady-state laminar flow[5]; (b) axial symmetry; (c) optically thin; (d) negligible viscous dissipation; (e) negligible displacement current and flow-induced electric field; (f) local thermodynamic equilibrium for the ionization[6], while the dissociation and recombination rates of hydrogen

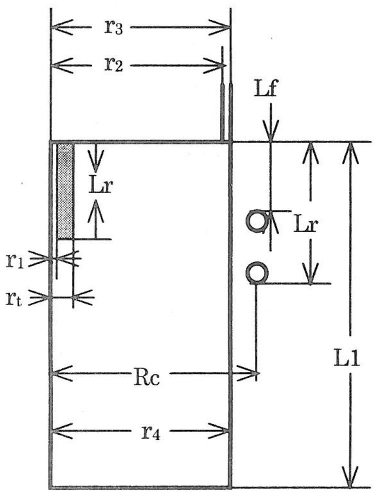


Fig.1 Geometry of the calculation domain of the RF plasma torch

**Table 1 Parameters of the RF plasma torch**

| | |
|---|---|
| Torch power | 60.0 kW |
| Working frequency | 0.5 - 4 MHz |
| Pressure | 101.3 kPa |
| Coil radius (Rc) | 56.5 mm |
| Coil turn number | 2 |
| Distance to frontal end of coil (Lf) | 23 mm |
| Distance to rear end of coil (Lr) | 80 mm |
| Wall thickness of quartz tube (w) | 1.5 mm |
| Insertion length of steel tube (Lt) | 45 mm |
| Torch length (L1) | 240 mm |
| Flow rate of carrier gas (Ar) | 2 liters/min |
| Flow rate of sheath gas (Ar) | 20 liters/min |
| Flow rate of sheath gas ($H_2$) | 2.65 liters/min |
| Inner radius of injection tube (r1) | 1.0 mm |
| Outer radius of injection tube (rt) | 4.5 mm |
| Inner radius of outer slot (r2) | 39 mm |
| Outer radius of outer slot (r3) | 41 mm |
| Inner radius of quartz tube (r4) | 55 mm |

have been considered.

The fields of flow, temperature and concentration of the RF thermal plasma can be calculated by solving the two dimensional continuity, momentum, energy and species conservation equations in consideration of swirl flow o  the sheath gas.

Continuity: $$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

where $\rho$ is the density, **u** is the velocity.

Momentum: $$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \tau + \mathbf{J} \times \mathbf{B} \quad (2)$$

where p is the pressure, $\tau$ is the viscous stress tensor. The last term in the right-hand side is due to the Lorentz force.

Energy:

$$\rho \mathbf{u} \cdot \nabla h = \nabla \cdot \left( \frac{k}{Cp} \nabla h \right) + \nabla \cdot \left\{ \frac{\mu}{Pr} \sum_i (Le_i - 1) h_i \nabla c_i \right\} - Qr + \mathbf{J} \cdot \mathbf{E} \quad (3)$$

where h is the enthalpy, k is the thermal conductivity, $C_p$ is the specific heat at constant pressure, $Q_r$ is the radiation loss per unit volume, and c is the mass fraction. The second term in right-hand side is due to the energy transfer caused by diffusion, and the last term is due to the Joule heating.

Species: $$\rho \mathbf{u} \cdot \nabla c = \nabla \cdot (\rho D \nabla c) + S \quad (4)$$

where D is the diffusion coefficient and S is the source term owing to the dissociation and recombination of hydrogen. In these equations, the conduction current **J**, the magnetic flux density **B**, and the electric field intensity **E** have been obtained from Maxwell's equation.

The boundary conditions along the centerline were set to insure axial symmetry. The temperature at the inside wall of the plasma torch was calculated assuming the outside wall was at 300 K by water cooling. The injection tube was assumed to be at 500 K. Each gas stream has constant axial velocity with zero radial velocity having temperature 300 K.

The electromagnetic (EM) fields in this study have been analyzed on the basis of the two-dimensional modeling approach with the electric field intensity as the fundamental EM field variable[7]. Maxwell's equations are expressed in terms of the electric field intensity as follows:

$$\nabla E - \xi \sigma \frac{\partial E}{\partial t} = 0 \quad (5)$$

where $\xi$ is the magnetic permeability and $\sigma$ is the electrical conductivity.

The recombination rate $k_r$ of hydrogen[8] considering the three-body reactions with neutral species M can be evaluated from Eq.(6):

$$H + H + M = H_2 + M \qquad (6)$$

$$k_r = 1.0 \times 10^6 T^{-1.0}$$

The dissociation rate has been calculated using the equilibrium constant.

The governing conservation equations have been solved SIMPLEC algorithm[9], which is revision of SIMPLER (Semi-Implicit Method for Pressure Linked Equation Revised) algorithm[10]. The governing equations and the electric field intensity equation were discretized into finite difference from using the control-volume technique.

## III. EXPERIMENTAL

The magnetic fields are applied from the coils of 3～12 turns which is according to the induction frequency. The flow rates of the sheath gas (Ar), the sheath gas ($H_2$) and the carrier gas are 70, 20, 0 liters/min., respectively. An RF amplifier which is enable to change the oscillation frequency of 0.5, 1, 2 and 4 MHz and with a maximum RF power of 100kW is used for generating RF magnetic field. The observations of the plasma region are performed using an air-cooled CCD camera system which is monitoring the total emissions (from 300 nm to 1 $\mu$ m) from the plasma. The emission region can be regarded as the plasma region. An Ar-$H_2$ atmospheric pressure plasma is successfully operated at 0.5 MHz frequency and up to 75 kW RF power condition.

## IV. RESULTS AND DISCUSSIONS

The calculated isotherms at the induction frequencies of 0.5 and 4 MHz are shown in Figs. 2 and 3, respectively. The temperature fields show off-axis peak distribution, because the time-varying magnetic field cannot penetrate into the inner part of the plasma. This phenomenon is quantified in terms of the skin depth $\delta$ defined as

$$\delta = (\pi \xi \sigma f)^{-1/2} \qquad (7)$$

where f represents the induction frequency. The skin depth indicates the penetration depth of the time-varying magnetic field into the plasma. The skin depth increases with a decrease in the frequency. At lower induction frequency, the high temperature region in the plasma exists more inside than at higher induction frequency. Furthermore, at lower frequency, low temperature region spread near the torch wall inside the induction coil. It is said that the lower induction frequency leads the narrower and longer plasma region.

Figures 4 ～ 6 indicate the comparisons of the observed plasma regions between the

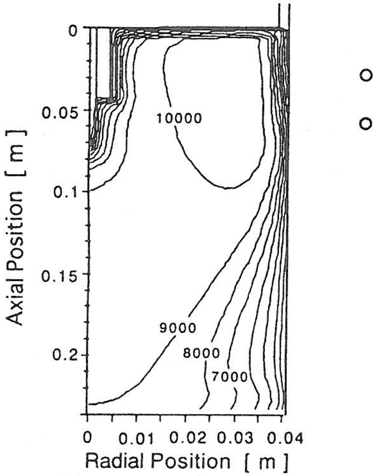


Fig. 2 Isotherms in Ar-$H_2$ plasmas at 4 MHz.

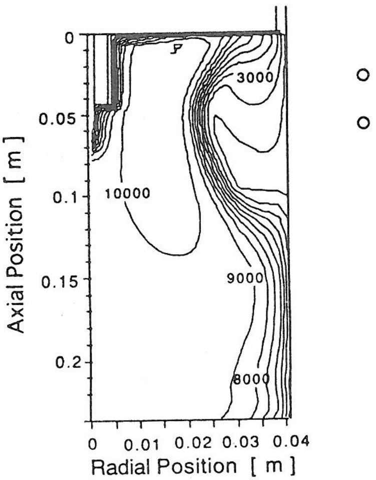


Fig. 3 Isotherms in Ar-$H_2$ plasmas at 0.5 MHz

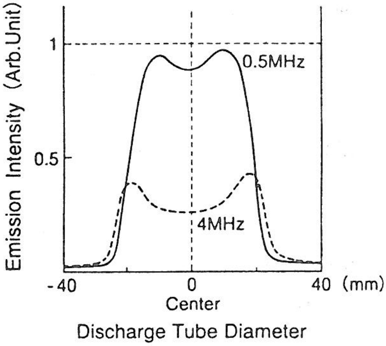


Fig. 4 Emission distributions at 25 mm upstream from middle of coil region.

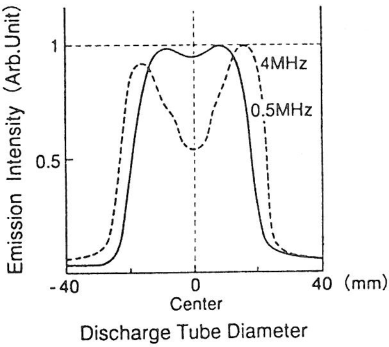


Fig. 5 Emission distributions at middle of coil region.

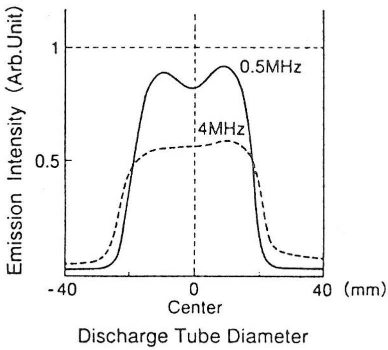


Fig. 6 Emission distributions at 30 mm downstream from middle of coil region.

induction frequencies of 0.5 and 4 MHz. The 12- and 3-turn-coil are used for the 0.5 MHz and 4 MHz operations, respectively. The applied RF power is 40 kW. The radial distributions of the emission intensity are normalized based on the maximum intensity at the middle part of each induction coil. The left and right axis of the figures indicate the wall of the quartz discharge tube. In the case of 4 MHz, the emission intensity abruptly decreases away from the middle part of the coil region. On the other hands, in the case of 0.5 MHz, the degradation of the emission intensity along the axis is less and the width of it is slightly narrower than at higher frequency. Lower induction frequency generates longer and narrower plasma region.

These experimental tendencies coincide comparably with the calculated isotherms. A decrease in the induction frequency leads to an increase in the skin depth, resulting in the deep penetration of the high temperature region, namely, the plasma region.

## V. CONCLUSIONS

Comparisons of numerical and experimental results of the effect of the induction frequency on the plasma region have been performed. The induction frequency has a strong influence on the size and shape of the plasma. A decrease in the frequency leads to an increase in the skin depth, therefore the peak position of the temperature distribution shifts toward the center with a decrease in the frequency. The choice of the induction frequency is important in determining the optimum torch diameter.

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