Plasma Analysis Method For Electrodeless Discharge Lamp Using 3-D FEM

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Abstract — This paper proposes a plasma analysis method for inductively coupled electrodeless discharge lamp using 3-D finite element method (FEM). To enhance the light emitting efficiency, electron density is analyzed by using the plasma analysis method coupled with the magnetic field and electron diffusion equation. The distribution of electron density is clarified.

I. INTRODUCTION

Recently, computer simulations are widely used in various engineering fields because of the significant improvement of computer performance, and can be applied to complex phenomena. We have also reported the magnetic field analysis method coupled with the current distribution, the electric circuit, the motion, the heat transfer equation and so on in order to design the electromagnetic devices and to clarify the complex phenomena [1][2].

On the other hand, an inductively electrodeless discharge lamp, which has several advantages such as high efficiency and long life, is required moreover to enhance the light emitting efficiency in response to energy conservation. In the light emitting process of this lamp, the electric energy is transmitted to the plasma by the magnetic coupling, and the ultraviolet light of excited liquid silver is transformed to the visible light on the phosphor. It is very important to compute the electron density distributions in order to enhance the performance at each process [3].

In this paper, we propose a plasma analysis method coupled with the magnetic field and the electron diffusion equation using 3-D FEM.

II. ANALYSIS METHOD

The distribution of electron density is changed by the influence of electromagnetic field. The electromagnetic field is also changed by the distribution of electron density. Then the coupled method is required to accurately compute the plasma phenomenon. Figure 1 shows the flowchart of proposed method.

A. Magnetic Field Analysis

The fundamental equation of the magnetic field can be expressed in frequency domain as follows.

$$\begin{cases} \mathrm{rot}\left(\dot{\nu}\,\mathrm{rot}\,\dot{\boldsymbol{A}}\right) = \dot{\boldsymbol{J}}_0 + \dot{\boldsymbol{J}}_e = \dot{\boldsymbol{J}}_0 - \sigma_p\left(j\omega\dot{\boldsymbol{A}} + \mathrm{grad}\,\dot{\phi}\right) \\ \mathrm{div}\left\{-\sigma_p\left(j\omega\dot{\boldsymbol{A}} + \mathrm{grad}\,\dot{\phi}\right)\right\} = 0 \end{cases} \quad (1)$$

Where $\dot{\nu}$ is the magnetic reluctivity, $\dot{\boldsymbol{A}}$ is the magnetic vector potential, $\dot{\boldsymbol{J}}_0$ is the exciting current density, $\dot{\boldsymbol{J}}_e$ is the eddy current density, σ_p is the electric conductivity in the plasma space, ω is the angle frequency, and $\dot{\phi}$ is the electric scalar potential.

By the way, the current density $\boldsymbol{J}_p$ flowing in plasma space is given as follows.

$$\boldsymbol{J}_p = -en_e\mu_e\boldsymbol{E} + en_i\mu_i\boldsymbol{E} \quad (2)$$

Where e is the elementary charge, n_e and n_i are the densities of electron and ion, μ_e and μ_i are the mobility of electron and ion, and $\boldsymbol{E}$ is the electric field.

Because of electric neutrality in the plasma space, relationships between electron and ion become $n_e \cong n_i$ and $\mu_e >> \mu_i$. It is therefore assumed that the induced current in the plasma space is almost an electron, and the conductivity in plasma space is given as follows.

$$\sigma_p = en_e\mu_e \quad (3)$$

When the initial electron densities are set to be a constant value and the subsequent ones are obtained form last value, the conductivity σ_p is calculated from equation (3). The current density $\boldsymbol{J}_p$ flowing in the plasma space is analyzed by substituting the conductivity σ_p in equation (1). The electric field in the plasma space is calculated as follows.

$$\boldsymbol{E} = \frac{\boldsymbol{J}_p}{en_e\mu_e} \quad (4)$$

B. Electron Diffusion Analysis

We assume a bipolar diffusion, which is occurred both an ionization caused by collision between electron and neutron and a recombination caused by collision on the tube wall. The diffusion equation of the electron density n_e can be expressed as follows.

$$D_a\nabla^2 n_e + \nu_i n_e = 0 \quad (5)$$

Where D_a is the bipolar diffusion coefficient and ν_i is the ionized frequency.

It is assumed that the mobility and the temperature of electron are larger than those of ions, and the bipolar diffusion coefficient is then approximated as follows.

$$D_a \cong \frac{kT_e}{e}\mu_i \quad (6)$$

Where k is the Boltzmann constant.

The ionized frequency is calculated from the thermal motion energy of electron. The electron temperature is calculated from the electric field obtained by equation (4).

C. Coupled Analysis

The electron density is uniformly distributed in initial condition. The electromagnetic field in plasma space is analyzed taking into account the induced current on the conductivity obtained from the electron density. The electron temperature and the ionized frequency are calculated on the basis of the electric field. The distribution of electron density is subsequently deduced by solving the diffusion equation. The computations of magnetic flux density and electron density are repeated until convergence in the electron density. As it is not easy to apply the Newton-Raphson method for the nonlinear plasma analysis, an under-relaxation iteration (URI) method is applied to this method.

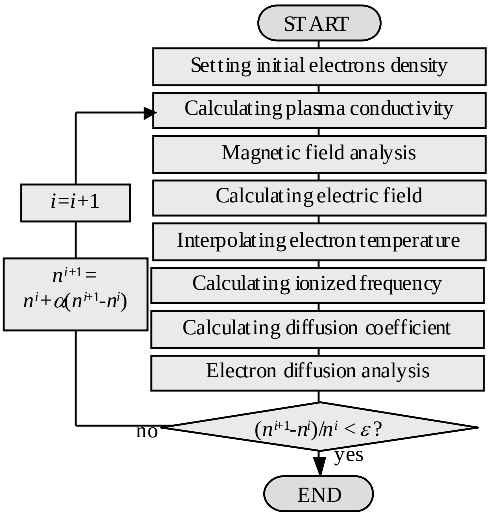

Fig.1 Flowchart of plasma analysis method

III. ANALYZED MODEL AND CONDITION

The inductively coupled electrodeless discharge lamp consists of spherical shape bulb which is applied a phosphor on the inside, induced coil and ferrite core. There is the cavity, where the induced coil and the ferrite core are set in, in the center of bulb. There are Ar and Hg gas in the spherical shape bulb to make the plasma phenomenon.

As the induced coil is excited at frequency of 135 kHz, the electron in bulb is accelerated by the high frequency electric field, which is induced in the bulb. As the ionization and the excitation are caused by the electron obtained the energy, the ultraviolet light radiated is transformed to the visible light on the phosphor. In this analysis, the plasma phenomenon till the electron is ionized is computed using 3-D FEM coupled with the magnetic field and the electron diffusion equation.

The magnetic field and electron diffusion analysis are carried out with the tetrahedral edge elements and tetrahedral nodal elements, respectively. The same mesh is therefore used in both simulations. The potentials on the surface of spherical shape bulb are fixed to be zero because the electron is recombined on the tube wall in the electron diffusion analysis.

IV. ANALYZED RESULTS

Figure 2 shows the distributions of electric field contour and electron density contour in the spherical shape bulb. The electric field intensity around induced coil becomes the largest of bulb due to the influence of induced current flowing in spherical shape bulb. The electron density in the center of bulb becomes the largest and approximately 4.0×10^{18} m^{-3}. Figure 3 shows the electron density characteristics. The electron densities on the axial location becoming the largest in electron density distribution are shown against parameter *r*, which is the distance from cavity in the radial direction. From this figure, it is found that the electron density becomes the largest at the location of 20 mm from cavity.

V. ACKNOWLEDGEMENT

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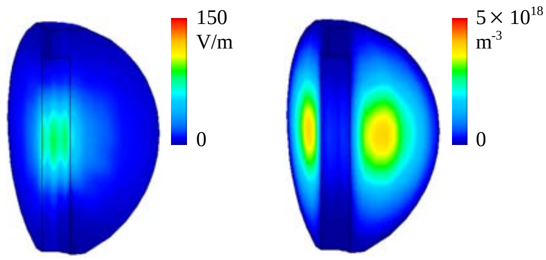

(a) electric field (b) electron density

Fig.2 Distributions of electric field contour and electron density contour in spherical shape bulb.

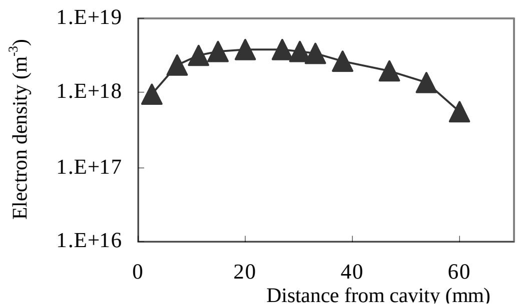

Fig.3 Electron density characteristics.

VI. REFERENCES

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