Abstract—We proposed an analysis method for plasma in an
electrodeless discharged lamp light-emitting by inductively-
coupled plasma, and a design of a power coupler was
investigated by focusing on the electric power from the exciting
coil to the plasma. We found that the power of the plasma was
increased and of an Al stage was decreased with moving the
core upward. This result suggests that the moving of the core
upward is effective to reduce wasted power loss by eddy
current and improves the lamp efficiency. In order to verify the
result, we changed the position of the power coupler in the
commercial lamp. Resultantly, the luminous flux of the lamp
was increased by approximately 150 lm (lumen), when the
power coupler was moved upward by 25 mm compared with
the position of a commercial lamp. Therefore, we can conclude
that our proposed method is applicable to the design of the
lamp and suitable design is important to obtain high lamp
efficiency.

Index Terms—Electrodeless discharged lamp, Inductively-
coupled plasma, High frequency excitation, electromagnetic field-
plasma interaction analysis.

I. INTRODUCTION

Recently, an electrodeless discharged lamp, which has
some industrial advantages such as long lifetime and
relatively high lamp efficiency, is used for a light source
with relatively high luminous flux such as a street lamp[1]. In
particular, the electrodeless lamp with an inner coil [2,3]
shows high lamp efficiency because driven frequency of
several hundred kHz is lower than RF band for outer coil
type[4]. Although the lamp with an inner coil is one of
hopeful candidates for new light source, its lamp efficiency
is approximately 90 lm/W and relatively low compared with
those for conventional lamps such as high-pressure sodium
ones (110 ~ 130 lm/W) and metal halide ones (70 ~ 130
lm/W), which prevents it from for further spread. In this
type of lamp, as the electric power is transmitted to the
plasma through the magnetic coupling, the state of the
plasma is strongly affected by magnetic factors such as
material, position and shape of magnetic core. A suitable
magnetic design that could supply much electric power to
the plasma is important to obtain the high lamp efficiency
because the light emission of the lamp originates from the
plasma. Therefore, development of an analysis method for
Inductively-Coupled Plasma (ICP) in the lamp is effective
to design the suitable lamp shape. Although some simulation
method for ICP were reported [4-6], analysis target of them is
RF-driven ICP such as plasma process and ion engine.
Therefore, we have developed a simulation method for low
frequency driven ICP in the lamp using Finite Element
method. In this study, in order to investigate the possibility
of improvement in the lamp efficiency, we focused on the
transmitted power to the plasma and investigated the suitable
design of the core in the lamp.

II. ANALYSIS PROCEDURE

A. Model lamp

Figure 1(a) shows an analysis object, which is a spherical
electrodeless discharge lamp (150W type) with an inner coil
produced by Panasonic Electric Works, Ltd. The lamp was
composed of a bulb and a power coupler. A phosphor
material was applied inner surface of the bulb. Ar gas and
amalgam (Hg-metal compound) were enclosed in the bulb,
and gas pressures under lighting were 23.2 Pa and 0.93 Pa
for Ar and Hg, respectively. The power coupler was
consisted of an Al die-cast, Cu tube, a ferrite core and
exciting coil. The Cu tube and the Al die-cast were used for
cooling of the core and a stage of the lamp, respectively.

B. Analysis procedure

Figures 1(b)-(d) and 2 show a model and the flow for the
analysis, respectively. 3D-analysis was carried out for the
bulb and the power coupler considering axial symmetry of
the lamp (Fig.1 (b)). For magnetic field analysis, vacuum
area and infinity boundary one were also modeled (Fig.1 (c)),
and then we divided those area to small elements (Fig.1 (d)).
An element size is approximately 1×1 mm and total element
number is approximately 30,000. After the settings of the
input electric power $P_{in}$ of 150 W and the initial value of the
plasma (electron) density $n_{e0}$ of $10^{19}$ m$^{-3}$, the high frequency
exciting current $I_0$ (135 kHz) of 2 A was given to the
exciting coil, and the FEM analyses of (1) the flux density $B$,
(2) the electric field $E$, (3) the electron temperature $T_e$ and
(4) the ionization frequency of the gas atom $v_i$ were carried
out in this order. $T_e$ and $v_i$ were obtained by the
experimental result between $E$ and $T_e$ in positive column and
the following equation, respectively.

$$v_i = 2 \cdot \frac{e}{m_e} \cdot \frac{a V_i^3}{3} \cdot (1 + 2 \cdot \frac{e V_i}{kT_e}) \cdot \exp\left(\frac{-kT_e}{eV_i}\right), \quad (1)$$

where $e$, $m_e$, $a$, $p$, $V_i$, and $k$ are the elementary electric
charge ($=1.602 \times 10^{-19}$ C), the electron mass ($= 9.109 \times 10^{-31}$

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kg), the

\begin{align}
D_a \frac{\partial}{\partial r} \left( r \frac{\partial n_e}{\partial r} \right) + D_a \frac{\partial^2 n_e}{\partial z^2} + v_i n_e = 0 ,
\end{align}

where \( D_a \) is bipolar diffusion coefficient. \( D_a \) in weakly-ionized plasma is given as

\begin{align}
D_a \approx \frac{k \cdot \mu_i T_e}{e} ,
\end{align}

where \( \mu_i \) is the mobility of Hg (\(=0.42 \text{ m}^2/\text{V} \cdot \text{s} \)). As the obtained distribution of \( n_e \) differs from the initial value \( n_{0e} \), the exciting current \( I \) was changed and the series of analyses from (1) to (5) were repeated until the power of the coil \( P_{\text{coil}} \) converges to \( P_{\text{st}} \). After conversion of \( P_{\text{coil}} \), the powers related to an eddy current loss in the plasma, the Cu tube and the Al stage areas were calculated and defined as \( P_p \), \( P_{\text{Cu}} \) and \( P_{\text{Al}} \), respectively.

In this analysis, an effect of the powers on the position of the core and the power coupler was investigated.

### III. RESULTS AND DISCUSSIONS

#### A. Analyzed Results

Dependences of the \( P_p \), \( P_{\text{Cu}} \) and \( P_{\text{Al}} \) on the top position of the core were shown in the Fig.3. Figure 4 shows schematic representation of analysis model. The position of 0 mm corresponds to the position for the commercial lamp. Increase in \( P_p \) and decrease in \( P_{\text{Al}} \) were observed by moving the core upward. As distance between the bottom of the core and the top of the Al stage is increased when the position is moved to upward, an eddy current in the Al stage is decreased. Figure 5 shows eddy current per unit volume in the power coupler. It is found that large eddy current flow at the top of the Al stage and Cu tube around the bottom of the core. Therefore, a design of the power coupler for reduction in the eddy current in the Cu tube and the Al stage enables us to improve the lamp efficiency, and we found that increase in the distance between the bottom of the core and the top of the Al stage is one of effective design to obtain the high lamp efficiency.
B. Experimental Result

In order to verify the analyzed result that upward-moved core is effective to improve the lamp efficiency, the position of the power coupler in the commercial lamp was changed from -5 mm to 25 mm, and the luminous flux $LF$ was measured at each position. As it is difficult to change the length of Cu tube in the commercial lamp, we changed top position of the power coupler. Figure 6 shows dependence of $LF$ on the top position of the core, together with the analyzed result for the power of the plasma $P_p$. $LF$ was increased with moving the power coupler upward and a good correlation was observed between $P_p$ and $LF$.

From abovementioned results, we can conclude that our proposed method is one of hopeful analysis method for the lamp and the design of increasing $P_p$ is effective to improve the lamp efficiency.

IV. CONCLUSION

In this paper, we developed a simulation method for low frequency driven ICP in the spherical electrodeless discharged lamp with an inner coil and investigated the suitable lamp design to improve in the lamp efficiency. The obtained results are summarized as follows;

(1) Increase in the distance between the bottom of the core and the top of the Al stage is one of effective design to obtain the high lamp efficiency because large eddy current flow at the top of the Al stage.

(2) Large eddy current in Cu tube was observed around the bottom of the core, and we need to reduce the eddy current in this part especially to improve in the lamp efficiency.

(3) Luminous flux of the commercial lamp was increased with moving the power coupler upward and we confirmed a good correlation was observed between analyzed power of plasma and measured luminous flux of the lamp.

Our future work is detail investigation of the design in the bulb and the power coupler of the lamp to obtain high lamp efficacy.

REFERENCES