Research Note

Investigation on the Minimum Maintenance Discharged Power of a Low-Frequency Driven Electrodeless Compact Fluorescent Lamp - Buffer Gas and Driving Frequency Dependence -

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ABSTRACT

We have investigated the minimum discharged power to maintain lamp plasma in terms of dependence on buffer gas condition and driving frequency of the electrodeless compact fluorescent lamp (ECFL). It is essential for realization of the low-frequency driven ECFL with inductively coupled plasma technique for household use. Considering the point of cost, the driving frequency of the electrodeless discharge lamp should be lowered because high frequency driving (>1MHz) requires special components for reduction of EMI noise and circuit power loss with the increase in driving frequency. But it is difficult to maintain plasma at low frequency driving, since induced electric fields, which excited with the induction coil is declined and not receive energy for ionization and discharge sufficiently. Here, we indicated that the condition of minimum power to maintain the H-mode (inductively coupled) discharge described as simple functions of buffer gas pressure and driving frequency for a fixed lamp bulb shape and found that the relation can represent the measured data well. Using that relation, we can easily predict optimum buffer gas pressure from driving frequency and required minimum maintenance power on the commercially available (practical) standpoint.

KEYWORDS: electrodeless, compact fluorescent lamp, low-frequency driven, buffer gas

Introduction

Recently, compact fluorescent lamps become widely used as growing of requirements for high efficacy and long lifetime, and also it raise expectations for more energy- and resource-saving performance. Meanwhile, electrodeless discharge lamps become to get a lot of attention as a long life light source. Until now, there are few electrodeless lamps which can be substituted for incandescent lamps. So, we developed an electrodeless compact fluorescent lamp with inductively coupled discharge technique.

In terms of economic product cost for household use, driving frequency of the electrodeless discharge lamp should be lowered because high frequency driving (>1MHz) requires special components to reduce the EMI noise and decrease circuit loss according to driving frequency ascendant. It is, however, difficult to obtain enough electric field to maintain a discharge from inductive coil at low power. Thus it is necessary to improve the plasma efficacy of the discharge bulb that enables to maintain a stable discharge. Inductively coupled electrodeless lamp with inner induction coil set in a cylindrical re-entrant cavity [8] has an advantage for low frequency driving comparately. It makes possible to insert a magnetic core in the induction coil windings. The magnetic core increases the inductance of the coil so much that the lamp can be driven by low frequency with lower current of the coil. In such a configuration, the discharge space is limited within the outer envelope and the cavity wall. Since a reduced discharge space, such as the diameter of outer bulb is limited on demand for downsizing and it needs a space for the cavity, enhances wall loss (by ambipolar diffusion) of the plasma. To reduce the wall loss, the outer envelope should be large and the cavity diameter should be preferably small. However, outer bulb size is demanded as small as incandescent lamp for replacement, and cavity size is restricted by the cross section of the magnetic core so as to avoid magnetic saturation. Hence, it is not probable to expand the wall distance freely. We investigated the buffer gas and driving frequency condition to cope with the maintenance of lamp plasma, so as to realize the low-frequency driven (< 500 kHz) electrodeless compact fluorescent lamp for household use with reduced cost.

2. Construction of our product

The structure of our product is shown in Figure 1. An induction coil with magnetic core is set in a cylindrical cavity. The inner surface of the envelope and the cavity are coated with a phosphor layer. Rare gas as buffer and mercury (Hg) as light-emitting material are sealed in that lamp bulb. Relatively low-frequency (< 500 kHz) alternating current is supplied from electronic ballast to the induction coil. Electrons were accelerated by the induced electric field and
Figure 1. Schematic diagram of the low-frequency driven electrodeless compact fluorescent lamp

Figure 2. Schematic illustration of the experimental set-up and specification of measurement instruments

come into collision with Hg atoms, then Hg atoms are excited mainly to a certain energy level (6P$^2$) and ultra violet (253.7nm) radiation is emitted when they are de-excited. That ultra violet emission is converted to a visible light by a phosphor layer.

In such a low driving frequency, it becomes difficult to maintain steady-state discharge especially by low input power, because the induced electric field is proportional to the frequency. Electrons obtain energy for ionization from electric field decided by energy balance for maintains discharge and that electric field are produced by induced electric field. Therefore the conditions for plasma maintenance should be more severe than those for high frequency (2.2 MHz~13.56 MHz) driving which is commonly used.

In order to reduce the electric field for plasma maintenance, rare gases, which have larger collision cross section, are usually employed as buffer gas. It makes ambipolar diffusion loss decline since the larger cross section prevent the more electrons and ions toward the wall, with the result that it is not necessary to generate more electrons and ions and to emphasize the electric field for maintaining discharge. So we used Krypton although Argon is generally adopted as a buffer gas for fluorescent lamps.

3. Experimental set-up

A schematic diagram of the experimental setup is shown in Figure 2. A sinusoidal current is generated by an oscillator (NF CORPORATION type WF1943) and transferred to matching circuit through an amplifier (NF CORPORATION type HSA4052). A digital power meter (YOKOGAWA type PZ4000) set up between amplifier and matching circuit, and a power consumption lamp is measured as a sum of matching circuit loss, induction coil loss and transferred power into the lamp bulb. The reason is that it is difficult to measure the input power of plasma, directly. Moreover measuring voltage, current and phase factor at both ends of the induction coil fairly include observation error. The phase difference between the voltage and the current at the induction coil is closed to 90 degree, so that the reading error of the phase difference has much effect on the evaluation of electric power. Therefore we measured consumed power at the input terminal of the matching circuit (including the matching circuit and induction coil loss. Matching circuit is composed of capacitors, which are commonly used commercial items, combined series and parallel (two capacitance are connected as shown Figure 2). The constants
of capacitor elements are determined to maximize the power factor (impedance matching) at driving frequencies. The lamp bulb is made by 0.8 mm thickness soda lime glass. The shape of the bulb is analogous to an incandescent lamp, and the outer diameter is 65mm and the height is 70mm. The re-entrant cavity with 21mm diameter has the height of 60mm. Inner surface of the lamp bulb is coated with a phosphor layer to convert ultraviolet rays (mainly 253.7nm) to visible rays. Krypton (120–350Pa) and mercury are filled in the lamp bulb. The vapor pressure of mercury is controlled by the temperature of the coolest portion of the bulb. Since mercury vapor pressure is sensitive to the temperature and has much effect on discharge condition, we maintain a constant temperature of 25 ± 1 °C to avoid the influence of the temperature fluctuation. Induction coil consists of the 60 turns windings of Litz wire wound around a magnetic core (Mn-Zn ferrite), and has a cylindrical shape (outer diameter is 13.5mm, inner diameter is 6.5mm and height is 45mm). An exhaust tube of the lamp bulb is inserted into the center of the core. The coil inductance is 390μH and the resistance is 0.7Ω at 100kHz (measured by LCR meter HEWLETT PACKARD type 4284A at room temperature).

4. Observation of the plasma maintenance power
In the case of inductively coupled discharge lamps, there are two discharge modes between which sudden transition is observed. One is capacitive coupling discharge (E-mode) with quite low current in lamp plasma. Another is inductive coupling discharge (H-mode) in which plasma is high density and commonly used for light sources. Therefore the minimum power to keep the H-mode discharge is quite important to obtain stable-state discharge. We thus measured the minimum power to maintain the discharge plasma including the matching circuit and induction coil loss.

Firstly we warmed the lamp for a time to reach stable state at which the bulb cold spot temperature was 47 °C. Then we reduced the input power gradually until mode jump (from H-mode to E-mode) was observed. We measured the adjacent consumption power before turning to E-mode discharge as minimum power for maintaining plasma.

Figure 3 shows a minimum plasma maintenance power ($P_{min}$) as a function of driving frequencies ($f$). As is evident from figure 3, $P_{min}$ decreases in proportion to the inverse square of the frequency for a fixed bulb shape at any frequencies under 500kHz. This is because the electric field in discharge vessel comes up in proportion to the driving frequency according to Faraday's law. Electrons are able to obtain enough energy of ionization from electric field, so that the ionization rate grows up as energy increasing and make it easy to maintain a discharge.

Figure 4 shows a minimum plasma maintenance power dependence on buffer gas pressure ($P_{buf}$). As seen in the previous result, minimum plasma maintenance power decreases with increasing buffer gas pressure. It is because that the electron loss (at the wall of lamp bulb) decreases whereby increasing a buffer gas pressure. Electrons are mainly transported by ambipolar diffusion to the envelope and cavity wall. If a buffer gas pressure is high enough, then the transportation of electrons is disturbed by the presence of neutral particles. Therefore, electron loss is smaller than that of low buffer gas pressure as going toward wall is thwarted by the presence of neutral gas and it gets easier to maintain discharge plasma.

One can see from results displayed in figure 3 and figure 4 that higher frequency and buffer gas pressure are advantageous to reduce a plasma maintenance power.

5. Discussion
Here we discuss the influences of driving frequency and buffer gas pressure on the discharge condition. In discharge space, to produce and maintain the plasma, it is needed that ionization and wall loss by ambipolar diffusion are balanced.
eq. (1) is well-known equation of particle conservation, [2]

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{u}_e) = G - L
\]

(1)

where \(n_e, \mathbf{u}_e, G\) and \(L\) are electron number density, mean particle velocity, creation and destruction rate of particles (e.g., ionization and recombination), respectively. For common low-pressure discharges in the steady state, \(G\) is usually due to ionization by electron-neutral particle collision : \(G = \nu_{ix} n_e\), here \(\nu_{ix}\) is the ionization frequency. In our case, Hg atoms mainly contribute to ionization. It is because the ionization energy of Hg (10.43eV) is lower than that of Kr (13.96eV). The volume loss rate \(L\) usually due to recombination, is often negligible at low-pressure discharge as the rate of recombination by volume loss is much smaller than that of wall loss. Hence, in typical discharge, eq. (1) is transcribed simply:

\[
\nabla \cdot (n_e \mathbf{u}_e) = \nu_{ix} n_e
\]

(2)

In the case of cylindrical positive column, by solving the eq. (2) at the polar coordinates, the radial variation of the plasma density distribution is obtained to be described by a Bessel function as follows, [4]

\[
n_e = n_{e0} J_0 \left( r \sqrt{\nu_{ix}/D_a} \right)
\]

(3)

here \(n_{e0}, J_0(x)\), \(r\) and \(D_a\) are electron number density at tube axis, Bessel function of zero order, radial distance, ambipolar diffusion coefficient, respectively. Assuming electron density comes down to zero at the wall, above-mentioned Bessel function equal to 0 and we can described \(\nu_{ix}\) as follows, [5]

\[
\sqrt{\frac{\nu_{ix}}{D_a}} \approx 2.4
\]

\[
\frac{\nu_{ix}}{r_w} = 5.8
\]

\[
\mu = 5.8 \frac{k T_e}{e}
\]

\[
\nu_{ix} \approx \frac{5.8}{r_w} \frac{T_e}{p_{gas}}
\]

(4)

where \(n_{e0}, J_0, T_e, e\) and \(p_{gas}\) are discharge wall distance, ion mobility, Boltzmann constant, electron temperature, electron charge and neutral gas pressure, respectively.

Although above-described equations are the case of cylindrical positive column plasma, it can be used in the circumferential discharge plasma around the induction coil observed in the electrodeless compact fluorescent lamp to consider the of plasma density, simply.

Once a bulb shape is fixed, eq.(5) follow from eq.(4) as \(r_w\) is constant. Here, \(p_{gas}\) is neutral gas pressure and is almost equal to that of buffer gas because of much lower mercury partial pressure. At a temperature of 320K, Hg pressure is about 1.4Pa and Kr pressure is hundred times higher than Hg pressure.

\[
\nu_{ix} \propto \frac{T_e}{p_{gas}}
\]

(5)

Also \(\nu_{ix}\) is shown by eq.(6) since making a contribution to ionization is not mainly buffer gas but mercury vapor,

\[
\nu_{ix} = n_{w-Hg} \sigma_{N-Hg} \langle v_e \rangle
\]

(6)

where \(n_{w-Hg}, \sigma_{N-Hg}\) and \(\langle v_e \rangle\) are neutral particle density of mercury, ionization cross section of mercury and mean electron velocity, respectively. Keeping the coolest temperature of bulb is almost the same, \(n_{w-Hg}\) would be constant. Therefore eq.(6) is rewritten to eq.(7).

\[
\nu_{ix} \propto \langle v_e \rangle \propto \sqrt{T_e}
\]

(7)

Consequently, eq.(8) as a condition of maintaining discharge derived from eq.(9) and eq.(7).

\[
\sqrt{T_e} = \text{Const.}
\]

(8)

\[
P_{gas} \approx \sigma \frac{E_m^2}{m_e v_e^2}
\]

(9)

Electron collision frequency \(v_e\) is as follows, where \(v_{en}, m_e\) and \(\sigma\) are electron-neutral particle (buffer gas) collision frequency, neutral particle density, and cross section of neutral particle.

\[
\nu_e = v_{en} + v_{ix} \approx v_{en} \left( \langle v_e \rangle \right) v_{ix}
\]

\[

\nu_e = n_e \sigma_e \langle v_e \rangle \propto p_{gas} \sqrt{T_e}
\]

(10)

Accordingly, plasma consumed power \(P_{in}\) is derived from eq.(8), eq.(9) and eq.(10) as following eq.(11)

\[
P_{in} \propto \frac{n_e}{p_{gas}} \frac{E_m^2}{2}
\]

(11)

Since \(E_m\) which is the electric field for maintaining discharge decided by energy balance in plasma, is supplied from the electric field induced by induction coil. Hence \(E_m\) is limited by a feed capability of induction coil. In fact, the discharge is not maintained if \(E_m\) require for the induced electric field beyond the supply limit of induction coil. In consequence, it depends on the performance of the induction coil that the boundary between H-discharge and E-discharge.
Basically, as the electron density \( n_e \) goes to small, \( E_{in} \) require for higher intensity to maintain H-discharge. However, the supply capacity of the induction coil has limitation, and that limitation restricts the maximum of \( E_{in} \). Since \( E_{in} \) become the maximum limited by supply capacity of the induction coil where H-discharge change to E-discharge, \( E_{in} \) is the same value in so far as using the same induction coil and the same driving frequency. Meanwhile, the mode-jump E-H discharge or H-E discharge depend on the number of electron density. Once an induction coil and a bulb (plasma) shape are fixed, the condition of electron density, which decides to change H-mode to E-mode, is the same state. Therefore, \( n_e \) gets into the same value at the boundary between H-discharge and E-discharge. Consequently, we obtained \( P_{min} \) as the following eq.(12) at the fixed induction coil, bulb shape and driving frequency. \( P_{min} \) means consumed power at plasma just before changing mode H-discharge to E-discharge.

\[
P_{min} \propto \frac{1}{P_{gas}^2} \frac{1}{f^2}
\]  

(12)

Meanwhile, we try to consider the driving frequency, \( f \). In the case of the bulb shape and the buffer gas pressure are fixed, the electric field \( E_{in} \) is decided only by energy balance for maintaining discharge. Since \( E_{in} \) is only sourced from \( E_{ind} \) which is induced by the induction coil and, \( E_{ind} \) is proportional to \( f \) due to Faraday's law. Therefore we can obtain the relational expression, eq.(13) and eq.(14).

\[
E_{in} \propto \frac{E_{ind}}{f}
\]  

(13)

\[
P_{min} \propto \frac{1}{f^2}
\]  

(14)

Consequently the minimum power for discharge can be written as follows eq.(15), where \( A \) and \( B \) are constant.

\[
P_{min} = A \frac{1}{P_{gas}^2} \cdot \frac{1}{f^2} + B
\]  

(15)

We tried to plot Figure 5 using data that are previously shown in Figure 3 and Figure 4. It shows minimum power of maintenance discharge in a function of Kr-pressure (120Pa to 350Pa) and driving frequency (90kHz to 500kHz) with a fixed bulb shape. As a result, by using the least square fit to these data with eq.(15) above, we determined these constant as \( A = 9.68 \times 10^{-4} \) and \( B = 8.34 \). It was found that data almost coincides with theoretical curve denoted. The region of smaller \( P_{gas}^2 f^2 \) of fitted curve seems to be out of alignment. Those point of data are virtually measured at high driving frequency (over 400kHz). It is considered that influence of frequency response of magnetic core (variation character of inductance) begin appearing.

6. Concluding remark
We have investigated a maintenance discharge condition which depended on a driving frequency and buffer gas (Kr) pressure about low frequency driven electrodeless compact fluorescent lamp.

We described a condition of minimum maintenance power as a simple function of \( 1/P_{gas}^2 \) and \( 1/f^2 \) derived from simple analysis (e.g. rate equation as particle conservation, and so on) for a fixed bulb shape. And we found that relation can represent the measured data well. Using that relation, we can predict optimum buffer gas pressure from driving frequency and required minimum maintenance power as commodity character.

References