Light & Engineering
Vol. 27, No. 6, pp. 133–136, 2019 *https://doi.org/10.33383/2018-064*

ELECTRODE-LESS UV LAMP ON THE BASIS OF LOW-PRESSURE MERCURY DISCHARGE IN A CLOSED NON-FERRITE TUBE

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ABSTRACT

Experimental study of characteristics of a non-ferrite electrode-less UV lamp with a length of 500 mm and width of 130 mm in the form of a closed quartz discharge tube with an inner diameter of 25 mm was conducted. The induction discharge was excited at a frequency of 1.7 MHz within the discharge lamp power P_{pl} ranging between 52 and 112 W in a mixture of mercury (~10^{-2} mm Hg) and argon (1.0 mm Hg) vapours by means of a 3-coil inductance located along the inner perimeter of the closed tube. With P_{pl} increasing: a) loss power in the inductance wire first decreased from 37 down to 22 W (P_{pl} = 84 W) and then increased up to 44 W; 2) the UV radiant flux of the lamp in a mercury light-band of 54 nm increased from 28 to 72 W; 3) radiant efficiency of the lamp at the light-band of 254 nm first increased from 31 to 48.5 % (P_{pl} = 84 W) and then slightly decreased down to 46 %; 4) radiant efficiency of the discharge plasma at the wavelength of 254 nm increased from 53 % to 65 %.

Keywords: UV radiation, induction discharge, closed tube, mercury lamp, low-pressure discharge plasma, inductance

1. INTRODUCTION

The low-pressure electrode-less mercury lamps are promising sources of UV radiation [1–4]. Due to lack of internal electrodes, they can operate at relatively low pressures of inert gas (0.05–0.5) mm Hg providing maximum radiant efficiency of the discharge plasma (η_{pl}) in mercury resonant lines of 185 and 254 nm [3, 4]. This provides a possibility to develop efficient resonance UV radiation sources within a wide range of power for water, air treatment, etc.

Of the special interest there is non-ferrite electrode-less lamps, in which high-frequency mercury plasma is excited in closed tubes by means of inductance located along the internal or external perimeter of the tube [5]. Such design allows going without ring-type ferromagnetic magnets decreasing reliability of the lamp's operation and increasing its cost. There are studies of the characteristics of non-ferrite electrode-less fluorescent lamps with closed glass discharge tubes with a relatively large diameter of (35–70) mm [5–7]. But the authors did

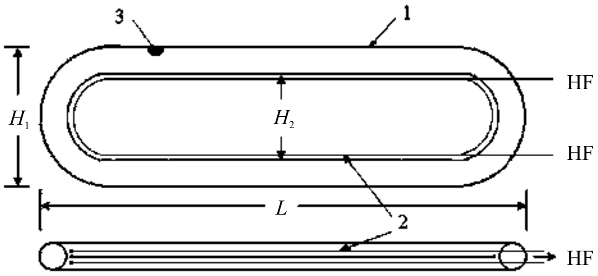

Fig.1. Scheme of the electrode-less non-ferrite lamp with closed discharge tube: *1* – discharge tube; *2* – inductance; *3* – amalgam; HF – high-frequency voltage

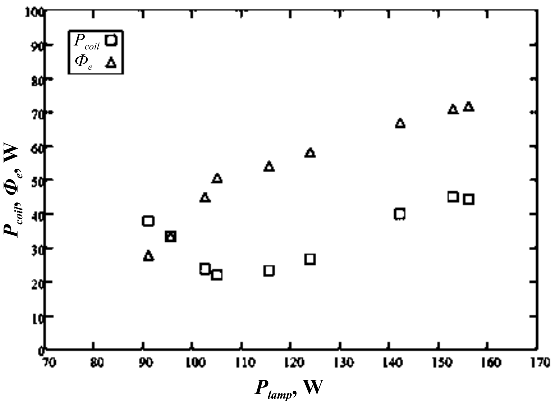

Fig. 2. Experimental dependencies of loss power in the inductance wire P_{coil} and lamp radiant flux at the 254 nm wavelength Φ_e on lamp power P_{lamp}

not manage to find publications on non-ferrite low-pressure electrode-less mercury lamps with closed quartz tubes used as UV radiation sources.

Below are the results of our experimental study of characteristics of a non-ferrite electrode-less mercury UV lamp with a closed quartz discharge lamp (bulb) with inner diameter of 25 mm, in which the plasma is excited by means of inductance located along the internal perimeter of the lamp.

2. EXPERIMENTAL INSTALLATION AND MEASUREMENT METHODS

The induction discharge was excited at frequency f equal to 1.7 MHz in a closed quartz tube with a wall thickness of 1.5 m and an inner diameter of 25 mm. The lamp had a form of a stretched ring with length L of 500 mm and width H_1 of 130 mm and distance between the long parallel sections of the discharge tube H_2 of 75 mm and the length of closed centre-line Λ_{pl} of 1060 mm (Fig. 1). HF inductor consisted of a 3-coil inductance made of copper wire with a diameter of 2.5 mm and specific resistance per length unit of 8×10^{-4} Ohm/cm located along the internal perimeter of the lamp. The mercury vapours pressure in the discharge tube was maintained optimal (with maximum radiant flux of the lamp Φ_e at the wavelength 254 nm) by means of temperature of mercury-indium amalgam located on the tube wall. *Ar* buffer gas pressure was equal to 1.0 mm Hg.

Φ_e was measured by means of an *IL1700* radiometer and *SED240/W* photometric head with cosine angular response [2]. The measurements were performed with package power P_k equal to (102–165) W and comprising: *a*) loss power of HF generator P_g; *b*) lamp power P_{lamp} comprising loss power of inductance wire P_{coil} and power of discharge plasma P_{pl}. The lamp was positioned in a black grounded box with a black screen in a plane normal to the lamp plane. There was a gap with a width Δ of 30 mm in the box for the lamp plane. The distance between the radiation detector (RD) and the gap d = 150 cm and the distance between the gap and the lamp ℓ = 10 cm, which allowed to consider the lamp section "cut out" by the gap as a point source of radiation [3]. Φ_e was calculated in accordance with [2, 3]:

$$\Phi_e = \pi^2 \cdot h \cdot d \cdot i \cdot L / (\Delta \cdot S), \qquad (1)$$

where $h = \ell + d$ is the distance between the lamp and RD, i is photocurrent of RD, S is total sensitivity of RD.

The value of the power generator efficiency η_g determined as $\eta_g = 1 - (P_g/P_k)$ was equal to 0.9 at frequency f of 1.7 MHz, and the value of P_{coil} was found using a substitution method without the discharge inside the lamp [5, 8].

3. MEASUREMENT RESULTS AND DISCUSSION

As it can be seen from the experimental dependencies of P_{coil} and Φ_e on P_{lamp} (Fig. 2), with increase of P_{lamp}: *a*) P_{coil} decreases from 39 W (P_{lamp} = 92 W) down to its minimum value of 22 W ($P_{lamp,\,min}$ = 105 W), then increases up to 44 W (P_{lamp} = 156 W); *b*) Φ_e "rapidly" increases from 28 W (P_{lamp} = 92 W, P_{pl} = 53 W) up to 45 W ($P_{lamp,\,min}$ = 105 W, $P_{pl,\,min}$ = 84 W), and then "slowly" up to 72 W (P_{lamp} = 156 W). Both dependencies are well correlated with each other.

As it can be seen from 3 other experimental dependencies (Fig. 3), with increase of P_{pl}: *a*) radiant efficiency of the lamp at wavelength 254 nm η_{lamp} ($\eta_{lamp} = \Phi_e/P_{lamp}$) increases from 32 % ($P_{pl}$ = 53 W) up to 46 % (P_{pl} = 84 W), and then insignificantly decreases down to 44 % (P_{pl} = 112 W); *b*) η_{pl} ($\eta_{pl} \approx \Phi_e/P_{pl}$) practically linearly increases from 52 to 66 %; *c*) Efficiency of the inductance η_{coil} ($\eta_{coil} = 1 - P_{coil}/P_{lamp}$) increases from 59 % ($P_{pl}$ = 53 W) up to 81 % (P_{pl} = 84 W) and then decreases down to 71 % (P_{pl} = 112 W). Also, we note that $\eta_{lamp} = \eta_{coil}\times\eta_{pl}$.

Increasing of P_{coil} with increasing of P_{pl} and corresponding decreasing of η_{coil} and η_{lamp} are related to skin effect in the HF induction discharge (with rather high density) at frequencies of hundreds of kHz and higher [9]. The skin effect is characterised by "pushing-put" of the HF electric field from the dense plasma area (near the centre-line of the tube) and its "pressing" to the walls of the discharge tube where the inductance wire is located and HF electric field density is maximum [10]. As a result, average density of HF electric field over the cross-section area $\bar{E}_{pl}$ of the discharge tube increases, HF voltage on the plasma coil U_{pl} rises ($U_{pl} = \bar{E}_{pl} \times \Lambda_{pl}$) and, therefore, in accordance with the transformer model of induction discharge, HF voltage and current of the inductance I_{coil} increase, therefore, P_{coil} ($P_{coil} = (I_{coil})^2 \times R_w$) where R_w is resistance of the inductance.

But the skin effect does not significantly affect the UV radiation generation which is witnessed by approximate linearity of the dependence $\eta_{pl}(P_{pl})$ within the whole studied range of P_{pl} (52–112) W.

It is worth noting that, screening of UV radiation by the coils of the inductance covering (3–5)% of the surface area of the discharge tube was not taken into account during calculation of η_{lamp}. As a result, part of UV radiation is absorbed by the inductance therefore the actual UV radiant flux of the lamp is less than the measured flux Φ_e in accordance with the formula (1). Subsequently, the clarified $\eta_{lamp} = \eta_{coil} \times \eta_w \times \eta_{pl}$, where $\eta_w \approx 1 - (d_w/\pi d_{tr})$ is the factor of screening of the discharge lamp by the inductance, d_w is the inductance wire diameter, d_{tr} is the external diameter of the discharge tube.

4. CONCLUSION

– High values of η_{pl} (60–65)% of the electrodeless non-ferrite lamp with a closed discharge tube with diameter of 25 mm operating at a frequency of 1.7 MHz and specific power of plasma (SPP) of (0.8–1.0) W/cm were acquired. These values exceed those of electrode-less non-ferrite linear UV lamps operating at a frequency of (1–4) MHz with SPP of about 1 W/cm [4] and transformer-type UV lamps operating at SPP of 1 W/cm with frequency of 265 kHz [2, 3].

– P_{coil} is relatively high, (20–50) W and η_{coil} is relatively low, (70–80)%. But thanks to high values of η_{pl}, the values of η_{lamp} are equal to (45–46)% with SPP of (0.8–1.0) W/cm, which is higher than those of non-ferrite linear electrode-less UV lamps [4, 11] and electrode tube UV lamps operating at frequencies of (20–80) kGz (low) [12].

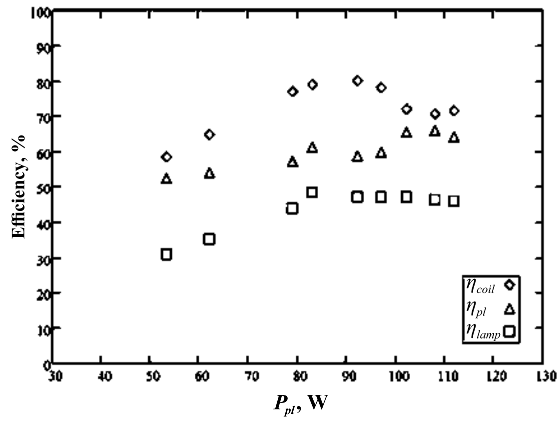

Fig. 3. Dependencies of the inductance efficiency η_{coil} and radiant efficiency of the lamp (η_{lamp}) and discharge plasma (η_{pl}) at the 254 nm wavelength on plasma power P_{pl}.

– η_{pl} may be increased by lowering the pressure of inert gas (*Ar*) down to (0.2–0.3) mm Hg. At such pressure, maximum efficiency of UV radiation generation by mercury plasma in a transformer-type lamp with a closed discharge tube and inner diameter of 16.6 mm was witnessed [3].

– η_{lamp} may be increased by increasing η_{coil} by decreasing P_{coil}. For this purpose the following actions may be taken: *a)* use a wire with low specific resistance per length unit for manufacturing of the inductance, < 3×10^{-4} Ohm/cm (litzendraht) [5, 6]; *b*) lower I_{coil} by increasing the number of coils up to 5–6 [13]; *c*) increase *of* up to (6–9) MHz [13].

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