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HIGH EFFICIENCY FERRITE-FREE CLOSED-LOOP INDUCTIVELY-COUPLED LOW MERCURY PRESSURE DISCHARGE UV LAMPS

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ABSTRACT

Radiation and electrical characteristics of ferrite-free closed-loop inductively-coupled low mercury pressure UV lamps of 375 mm in length and 120 mm in width were experimentally studied. Discharges were excited at a frequency of 1.7 MHz and lamp RF power, P_{lamp} = (95–170) W. It was in quartz closed-loop tubes of 16.6 mm in inner diam. and of 815 mm in length, in the mixture of mercury vapour (7 x 10^{-3} mm Hg) with *Ar* (0.7 and 1.0 mm Hg) and with the mixture of 30 % *Ne* + 70 % *Ar* (0,7 and 1,0 mm Hg). The 3-turn induction coil made from litz wire with a low specific linear resistance (ρ_w = 1.4 x 10^{-4} Ohm/cm) was disposed on the lamp surface along the closed-loop tube perimeter. In lamps with buffer gas pressure of 1,0 mm Hg, the increase of lamp power from 95 to 150 W caused the decrease of induction coil power losses, P_{coil}, from (6–7) W to (3–4) W. Also in these lamps increased induction coil power efficiency, $\eta_{coil} = 1 - P_{coil}/P_{lamp}$, from 92 % to 97 % and lamp UV radiation (λ = 254 nm) generation efficiency, $\eta_{e,\,254}$, from 57 % to 66 %. The decrease of buffer gas pressure from 1.0 to 0.7 mm Hg caused the decrease of $\eta_{e,\,254}$ by (10–20)%.

Keywords: ferrite-free inductively-coupled discharge, closed-loop tube, low pressure mercury plasma, induction coil, UV resonant radiation

1. INTRODUCTION

Electrode-less inductively-coupled discharges excited in the mixture of low pressure (~ 10^{-2} mm Hg) mercury vapour and inert gases (IG) are considered as very promising UV resonant (λ at 185 nm and 254 nm) radiation sources used in bactericidal lamps for air and water cleaning [1, 2]. Due to the absence of inner electrodes, these lamps have high lifetime and could be operated at low IG pressures ((0.1–1.0) mm Hg) at which UV radiation (λ = 254 nm) generation efficiency, $\eta_{e,\,254} = \Phi_{e,\,254}/P_{lamp}$ is the maximum. Here, $\Phi_{e,,254}$ is the lamp UV resonant (254 nm) radiation flux, P_{lamp} is the lamp power [3–5]. Due to these characteristics electrode-less inductively-coupled low pressure (LP) mercury UV lamps could be competitors to LP mercury UV lamps with inner electrodes operated at higher IG pressures of (2–3) mm Hg [6].

Of the special interest is the electrode-less ferrite-free inductively-coupled UV radiation lamps where LP mercury plasma is excited in the closed-loop quartz tube with the help of an induction coil of few turns positioned along the closed-loop tube perimeter [7, 8]. Recent experimental studies of this type of inductive lamps employing discharge tube with inner diameter d_t = 16.6 mm and 25 mm, operated at RF frequency of f = 1,7 MHz and plasma power per length unit, $P_1 = P_{pl}/\Lambda_{pl}$, have shown high UV radiation (254 nm) generation efficiency, $\Phi_{e,254}/P_{pl}$ = (63–65)% [9,10]. Here P_{pl} is the discharge

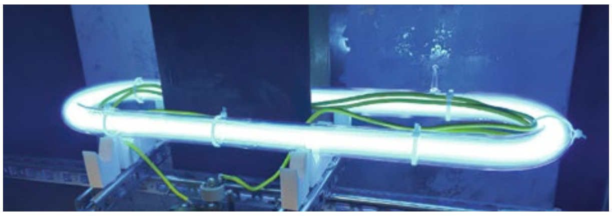

Fig. 1. Photo of ferrite-free closed-loop inductively-coupled mercury UV lamp

plasma power and Λ_{pl} is the plasma length. The latter is higher than that of LP mercury UV lamp with inner electrodes operated at f = 20 kHz [6], inductively-coupled ferrite-free linear mercury UV lamps operated at (1–4) MHz [5], and transformer-type (with circular magnetic coils) inductively-coupled mercury UV lamps operated at f = 265 kHz [3, 4].

However, because of high resistivity of induction coil single strand copper wire ($\rho_w = 8 \cdot 10^{-4}$ Ohm/cm), power losses in the induction coil were very high, P_{coil} in range (40–45) W, therefore, induction coil power efficiency, $\eta_{coil} = 1 - P_{coil}/P_{lamp}$, did not exceed 80 % and lamp UV radiation (254 nm) efficiency, $\eta_{e,\,254}$ was ~ 50 % [9, 10]. It appears to be obvious that to increase substantially η_{coil} (up to (95–97)%), one has to use in electrode-less inductively-coupled ferrite-free UV lamps an induction coil made from copper litz wire ((19–140) strands) that has at frequencies f = (0.2–2.0) MHz low resistivity, $\rho_w \leq 2 \cdot 10^{-4}$ Ohm/cm).

From practical point of view, it is interesting to study the possibility of developing high efficiency ferrite-free inductively-coupled LP amalgam UV lamps with closed-loop discharge tube with inner diameter of 16.6 mm capable to replace LP amalgam UV lamp with inner electrodes and discharge tube of the same diameter [6].

2. EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

An inductively-coupled discharge was ignited at the frequency of 1.7 MHz in the mixture of mercury vapour and buffer inert gases in the quartz closed-loop tube of 16.6 mm in inner diameter and 29 mm in outer diameter and of 815 mm in length (Fig. 1). The discharge was excited in the elliptically shaped experimental lamp (375 mm in length and 120 mm in width) using 3-turn induction coil made from litz wire ($\rho_w = 1.4 \cdot 10^{-4}$ Ohm/cm, d_w = 1.5 mm) positioned along the closed-loop tube perimeter (Fig. 1). Mercury vapour pressure was maintained optimal (maximum UV radiation flux, $\Phi_{e,\,254}$) and was controlled by the temperature indium-mercury amalgam disposed on the discharge tube wall inner surface. *Ar* and the mixture of 30 % *Ne* + 70 % *Ar* at pressures of 0.7 и 1.0 mm Hg were used as buffer gases.

The RF power generated by the power source, P_k is in range (107–190) W, included power losses in the generator, $P_{gen} = 0.1\ P_k$, and RF power consumed by the lamp, P_{lamp}. Since at f < 10 MHz, RF power losses in EM radiation are negligibly small [7]. The lamp RF power consisted of power losses in the induction coil wire, P_{coil}, and power absorbed by the inductive discharge plasma, P_{pl}. Coil power losses, P_{coil}, were measured directly in the power line in the absence of the plasma and at the coil current, I_c, equal to that in the presence of the plasma [4, 7].

The experimental lamp was installed in the black metal grounded box. The measurements were made using UV (254 nm) radiation receiver (SUV20) positioned near discharge tube walls. The receiver was preliminary calibrated using the standard etalon UV lamp with known UV radiation flux measured using the modified Keitz method [3].

3. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental dependencies of coil power losses, P_{coil}, from lamp power, P_{lamp}, obtained for two inductively-coupled lamps with two different fillings are shown in Fig. 2. It is seen that P_{coil} decrease from (7–8) W (P_{lamp} = 95 W) to (3–4) W (P_{lamp} =

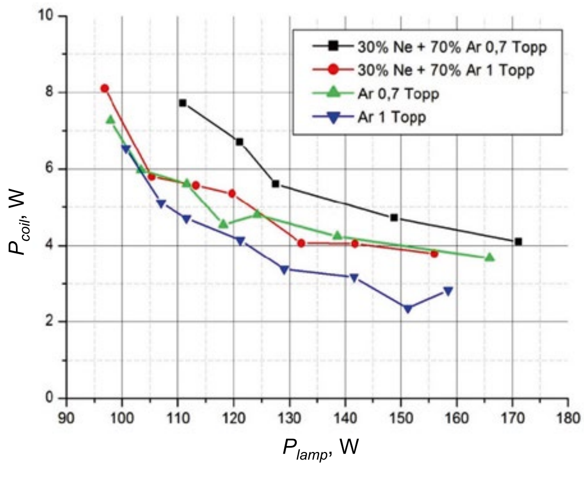

Fig. 2. Induction coil power losses, P_{coil}, as function of lamp power, P_{lamp}

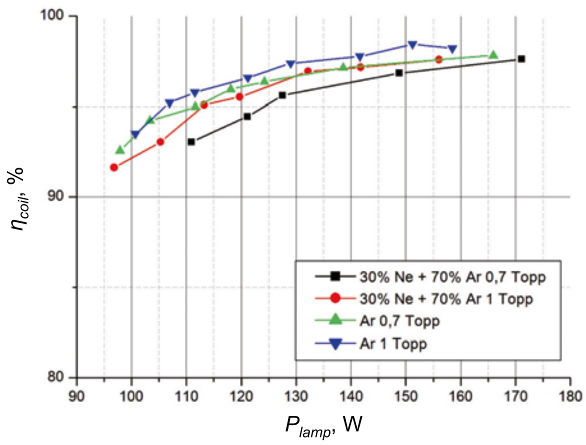

Fig. 3. RF inductor power efficiency, η_{coil}, as function of lamp power, P_{lamp}

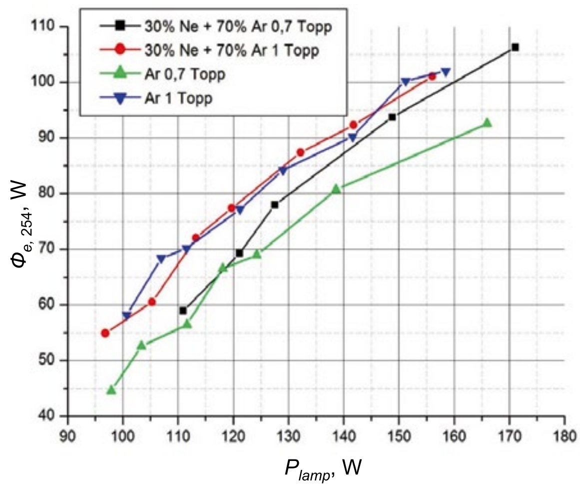

Fig. 4. Lamp UV resonant radiation flux, $\Phi_{e, 254}$, as function of lamp power, P_{lamp}

(140–150) W) and practically does not change at lamp power, P_{lamp} > 150 W. Reducing buffer gas as well as adding *Ne* to *Ar* causes insignificant decrease of coil power losses. Due to low coil power losses, induction coil power efficiency, η_{coil}, is high and grows with lamp power from 92 % (P_{lamp} = 96 W) to (97–98)% (P_{lamp} = 160 W), Fig. 3. These values are (25–30)% higher than for induction coils made from single copper wire of the same diameter, d_w, used in the induction ferrite-free lamps with discharge tube of d_t = 16.6 mm in diam. operated at frequency of 1.7 MHz and at the same lamp power, P_{lamp} [10].

The experimental dependencies of UV resonant radiation flux, $\Phi_{e, 254,}$ from lamp power, P_{lamp}, obtained in induction lamps filled with the mixtures of mercury vapour with *Ar* and with the mixtures of 30 % *Ne* + 70 % *Ar* at pressures of 0.7 and 1.0 mm Hg are presented in Fig. 4. It is seen that at pressure of 1.0 mm Hg, $\Phi_{e, 254}$ grows with P_{lamp} from 55 W (P_{lamp} = 95 W) to 102 W (P_{lamp} = 160 W) и exceeds by (10–20)% values of $\Phi_{e, 254}$ from lamps operated at IG pressure of 0.7 mm Hg.

Note that both in electrode-less ferrite-free inductive LP mercury UV lamps and in UV luminescent lamps with inner electrodes, the decrease of tube diameter, d_t, and plasma power, P_{pl}, shifts maximums of $\Phi_{e, 254}$ and Φ_v (luminous flux) to larger IG pressures [5, 11].

The experimental dependencies of UV (254 nm) radiation generation lamp efficiency, $\eta_{e, 254}$, from lamp power, P_{lamp}, are presented in Fig. 5. It is seen that the maximum value of $\eta_{e, 254}$, (64–66)% in the lamp with IG pressure of 1.0 mm Hg is achieved at lamp power, P_{lamp} equal to (120–160) W (P_1 = (1.5–2.0) W/cm). It is significantly higher than in ferrite-free inductive UV lamps with the same discharge tube characteristics but with an induction coil made of single copper wire having large resistivity, $\rho_w = 8 \cdot 10^{-4}$ Ohm/cm [9, 10]. From practical point of view, it is very important, that $\eta_{e, 254}$ of UV inductive lamps using induction coil made from litz wire by (30–40)% higher than that of mercury UV lamps with inner electrodes using discharge tube of the same diameter, d_t = 16.6 mm. At the same time, these lamps have the same lamp power, P_{lamp}, but higher IG pressures ((3–4) mm Hg) [6].

“Dilution” *Ar* with *Ne* does not affect UV efficiency, $\eta_{e, 254}$, of inductive lamps operated at IG pressure of 1,0 mm Hg. There are higher values of $\eta_{e, 254}$ in LP mercury inductive lamps with IG mixture (30 % *Ne* + 70 % *Ar*) at lower pressure, 0.7 mm Hg (Fig. 5), is, probably, due to higher plasma RF electric field and, thus, higher electron temperature in inductive discharge plasma.

It is important to note that UV lamp radiation flux, $\Phi_{e, 254}$, is actually smaller than measured in our experiment due to radiation multiple reflection from lamp tubes and radiation blocking effects with induction coil turns (Fig. 1). Therefore, to increase $\Phi_{e, 254}$ and, thus, $\eta_{e, 254}$, the number of coil turns, N, and coil wire diameter, d_w, should be reduced.

On the other hand, to ensure high induction coil quality factor, Q_{coil}, and low coil power losses, P_{coil}, the decrease of number of coil turns, N, should be accompanied by the increase of lamp driving RF frequency, f, [12]. However, the increase of RF frequency without proportional decrease of plas-

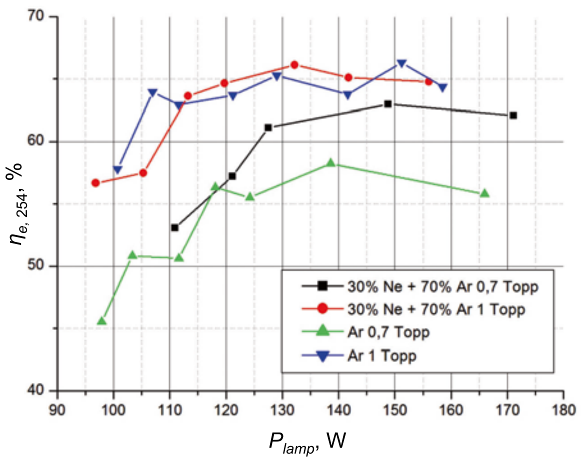

Fig. 5. Lamp UV radiation generation efficiency, $\eta_{e,\,254}$, as function of lamp power, P_{lamp}

ma density could cause a skin effect in the inductive plasma that "pushes" RF field to the tube walls and increases plasma RF electric field, E_{pl} [13–16]. As the result, $\Phi_{e,\,254}$, and lamp UV radiation generation efficiency, $\eta_{e,\,254}$, are increasing [9, 10], while by increasing induction coil power losses, $P_{coil} \sim \bar{E}_{pl}^2$, lamp UV efficiency, $\eta_{e,\,254}$, could stop growing and even could decrease as lamp power, P_{lamp}, grows [9, 10, 17].

CONCLUSION

– Due to employing in ferrite-free UV induction lamps with closed-loop discharge tube induction coils made from litz wire with low resistivity (ρ_w = 1.4·10^{-4} Ohm/cm), induction coil power losses are very low, P_{coil} = (3–7) W, while coil power efficiency is large, η_{coil} = (92–98)%.

– Lamp UV radiation generation efficiency is very high, $\eta_{e,\,254}$ = (62–66)%, which is higher than those of inductive lamps of the same type and with the same discharge tube parameters but using induction coils made from single copper wire with higher resistivity [9, 10]. Also, obtained in this study inductive lamp UV efficiency of (62–66)% is considerably higher than those of mercury UV lamps operated with inner electrodes [6].

– Addition of *Ne* (30 %) to *Ar* does not cause noticeable increase of $\eta_{e,\,254,}$ while IG pressure increase from 0.7 to 1.0 mm Hg causes growth of lamp UV efficiency, $\eta_{e,\,254}$, by (15–20)%.

– To reduce UV radiation flux blocking effects caused by the induction coil, it is recommended to decrease the number of coil turns, *N*, and/or coil wire diameter, d_w, while to maintain induction coil power losses at the same low level, lamp driving frequency, *f*, should be increased [12].

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