Light & Engineering
Vol. 28, No. 2, pp. 89–94, 2020
https://doi.org/10.33383/2019–040
Svetotekhnika #6, 2019, pp. 19–22

POWER LOSSES IN RF INDUCTOR OF FERRITE-FREE CLOSED-LOOP INDUCTIVELY-COUPLED LOW PRESSURE MERCURY LAMPS

Ekaterina V. Lovlya and Oleg A. Popov

National Research University Moscow Power Engineering Institute (NRU MPEI)
E–mail: popovoleg445@yahoo.com

ABSTRACT

RF inductor power losses of ferrite-free electrode-less low pressure mercury inductively-coupled discharges excited in closed-loop dielectric tube were studied. The modelling was made within the framework of low pressure inductive discharge transformer model for discharge lamps with tubes of 16, 25 and 38 mm inner diam. filled with the mixture of mercury vapour (7.5×10^{-3} mm Hg) and argon (0.1, 0.3 and 1.0 mm Hg) at RF frequencies of 1, 7; 3.4 and 5.1 MHz and plasma power of (25–500) W. Discharges were excited with the help of the induction coil of 3, 4 and 6 turns placed along the inner perimeter of the closed-loop tube. It was found that the dependence of coil power losses, P_{coil}, on the discharge plasma power, P_{pl}, had the minimum while P_{coil} decreased with RF frequency, tube diameter and coil number of turns. The modelling results were found in good qualitative agreement with the experimental data; quantitative discrepancies are believed to be due skin-effect and RF electric field radial inhomogeneity that were not included in discharge modelling.

Keywords: inductively-coupled discharge, closed-loop tube, low pressure mercury plasma, induction coil power losses

1. INTRODUCTION

Plasma of ferrite-free inductively-coupled discharges excited in mixture of low pressure (LP) mercury vapour and inert gases in closed-loop quartz tubes are considered as perspectives high efficient sources of UV radiation [1, 2]. Due to the absence of internal electrodes, electrode-less mercury UV lamps can operate at low buffer inert gas pressures of (0.1–0.5) mm Hg that provides maximum efficiency of resonant UV radiation [3].

Since electromagnetic radiation at frequencies of $f < 10$MHz is negligible [4], lamp RF power P_{lamp} is a sum of power absorbed by discharge plasma, P_{pl}, and power losses in coil wire, P_{coil} [5, 6]. Thus, to increase UV lamp efficiency one has to increase coil power efficiency $\eta_{coil} = (1 - P_{coil}/P_{lamp})$ [1], i.e. to minimise P_{coil}.

In the present work, effects of lamp parameters (discharge tube diameter, inert gas pressure, number of coil turns, N, operation frequency, f, and plasma absorbed power, P_{pl}) on coil power losses, P_{coil}, were theoretically studied with the help of transformer model of LP induction discharge [5, 6].

2. DISCHARGE TUBE AND RF INDUCTOR

The lamps studied had length (l_{lamp}) of 406, 426 and 454 mm and width (H_{lamp}) of 106, 126 and 154 mm, respectively. Discharge tube had inner diameter (d_t) of 16, 25 and 38mm and wall thickness (Δ) of 1.0, 1.5 and 2.0 mm, respectively. Induction coils of 3, 4 and 6 turns were made from multiple strand copper wire (Litz wire) with diameter (d_w) of 1.63 mm and resistance per unit length (ρ_w) of 8.5×10^{-4} Ω/cm (at f = (2–5) MHz). The coil turns were placed along the inner perimeter of the lamp that had "long" (l_{per}) length and "short" (H_{per}) length of 370 and 70 mm, respectively (Fig. 1).

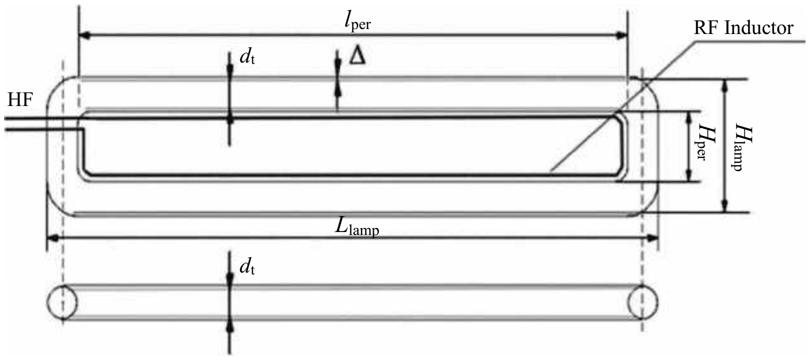

Fig. 1. Diagram of ferrite-free electrode-less inductively-coupled lamp with a closed-loop discharge tube and RF inductor (coil)

Mercury vapour pressure was 7.5×10^{-3} mm Hg (maximum UV radiation flux), inert gas (argon) pressures – 0.1, 0.3 and 1.0 mm Hg. Operation frequencies f are equal to (1,7–5,1) MHz, were chosen to satisfy condition $\omega << \nu_e$ (where $\omega = 2\pi f$ is the circular frequency of RF field, ν_e is the frequency of elastic collisions of electrons with mercury and argon atoms) that allows us to neglect the inductive component of plasma RF electric field. All calculation had been done at plasma powers P_{pl} in range (25–500) W.

3. PLASMA AND COIL PARAMETERS EQUATIONS

For calculation of plasma and coil electric parameters, the transformer model of LP induction discharge [5, 6] was used with assumptions of direct-current analogy [4] and RF electric field, E_{pl}, spatial (radial and azimuth) uniformity, and neglecting of skin-effect.

P_{coil} was calculated as

$$P_{coil} = I_{coil}^2 R_{coil}, \quad (1)$$

where I_{coil} is the RF current in the induction coil and R_{coil} is coil resistance calculated as

$$R_{coil} = \rho_w l_{coil}, \quad (2)$$

where l_{coil} is the length of coil wire defined as

$$l_{coil} = 2(l_{per} + H_{per})N. \quad (3)$$

In accordance with the transformer model of induction discharge, the expression for inductor RF current, I_{coil}, has the following expression [6]

$$I_{coil} = \frac{\bar{E}_{pl}\Lambda_{pl}\sqrt{1+Q_{pl}^2}}{\omega M}, \quad (4)$$

where Λ_{pl} is the length of plasma turn defined as length of centre line of the closed discharge tube, $\bar{E}_{pl}$ is the active component of plasma electric field averaged over cross-section of plasma turn, M is the mutual inductance of the plasma turn and the induction coil [5, 6]:

$$M = k\sqrt{L_{coil}L_{ind}}, \quad (5)$$

where L_{coil} is the inductance of disc shape induction coil ($D_{coil} >> H_{coil}$):

$$L_{coil} = 0,56\mu_o \pi D_{coil} N^2 \quad (6),$$

where $H_{coil} \approx d_w$ is the coil height, $D_{coil} = (4S_{coil}/\pi)^{1/2}$ is the coil equivalent diameter; k is the coupling coefficient of the plasma turn and the induction coil calculated as the ratio of the area encircled by the coil turn S_{coil} to the area encircled by the plasma turn S_{pl} [5, 6]:

$$k = \frac{S_{coil}}{S_{pl}},$$

where Q_{pl} is the plasma turn quality-factor that is defined as

$$Q_{pl} = \frac{\omega L_{ind}}{R_{pl}},$$

where $R_{pl} = P_{pl}/I_{pl}^2$ is the plasma turn resistance, I_{pl} *is* the discharge current, L_{ind} is the geometric inductance of plasma turn [7]:

$$L_{ind} = 2\pi D_{pl}\left[\ln\left(\frac{4D_{pl}}{0,39d_{pl}}\right) - 2\right]\cdot 10^{-9},$$

where $d_{pl} \approx 0,75d_t$ is the diameter of cross-section of plasma turn, $D_{pl} = (4S_{pl}/\pi)^{1/2}$ is the equivalent diameter of the area encircled by plasma turn, S_{pl} [8].

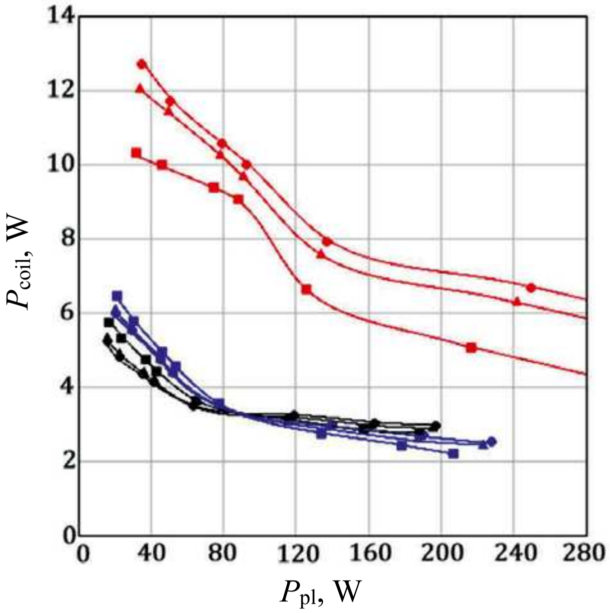

Fig. 2. Dependence of coil power losses, P_{coil}, on plasma power P_{pl}, tube diameter d_t, mm: 16 (red), 25 (blue), 38 (black); argon pressure p_{Ar}, mmHg: ● – 0.1; ▲– 0.3; ■ – 1.0; number of coil turns $N = 4$; RF frequency $f = 3.4$MHz

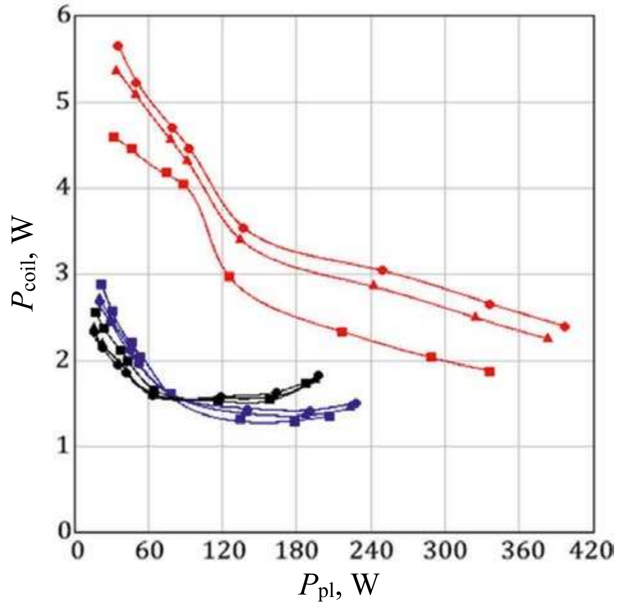

Fig. 3. Dependence of P_{coil} on P_{pl}, d_t, mm: 16 (red), 25 (blue), 38 (black); p_{Ar}, mmHg: ● – 0.1; ▲– 0.3; ■ – 1.0; $N = 4$; $f = 5.1$MHz

The equation that connects coil power losses, P_{coil}, with induction coil and discharge plasma parameters could be obtained from (1, 4):

$$P_{coil} = \frac{\left(\bar{E}_{pl}\Lambda_{pl}\right)^2 (1+Q_{pl}^2)\rho_w l_{coil}}{(\omega M)^2}\ . \qquad (7)$$

And using (3), (5), (6) and (7) one can get an expression that could be used for P_{coil} calculation:

$$P_{coil} = \frac{\left(\bar{E}_{pl}\Lambda_{pl}\right)^2 (1+Q_{pl}^2)\rho_w (l_{per}+H_{per})}{0{,}28\mu_o \pi D_{coil} N (k\omega)^2 L_{ind}}. \qquad (8)$$

With the approximation of direct-current analogy, we used values of electric field, E_{pl}, in the plasma positive column of argon-mercury discharge with the same tube diameter and fill pressure and operated at the same plasma power but at low frequency of 50 Hz [9].

4. CALCULATIONS RESULTS AND DISCUSSION

The dependencies of P_{coil} on P_{pl} calculated for lamps with various discharge tube and RF inductor parameters are shown in Fig. 2–5. It is seen that at relatively low values of P_{pl} values of P_{coil} in all lamps decrease considerably with P_{pl} increase. As P_{pl} grows the decrease of P_{coil} “slows down” and at a certain plasma power value, $P_{pl} = P_{pl,\,min}$, coil power losses reach their minimum value, $P_{coil,\,min}$, and then slightly increases with P_{pl}. The larger tube diameter, d_t, the lower value of $P_{pl,\,min}$ at which coil power losses reach their minimum value, $P_{coil,\,min}$.

The increase of RF frequency f causes the decrease of P_{coil} and shifts value of $P_{pl,\,min}$ to smaller values of P_{pl}. The effect of RF frequency on coil power losses can be explained by the transformer model of induction discharge excited at RF frequencies, $\omega \ll \nu_e$, which do not affect plasma power balance [4]. Therefore, $\bar{E}_{pl}$ and, hence, plasma turn RF voltage, U_{pl} (= $\bar{E}_{pl}\Lambda_{pl}$), do not depend from RF frequency ω. Note that in accordance with the induction discharge transformer model, coil RF voltage, U_{coil}, is related to U_{pl} as $U_{coil} \approx U_{pl}N/k^{1/2}$ [2, 6].

At the same time, coil inductive resistance, ωL_{coil} (here L_{coil} is coil conductance), increases linearly with the increase of RF frequency, $\omega = 2\pi$f. Since coil inductive resistance, $\omega L_{coil} \gg R_{coil}$, the induction coil impedance has inductive character so RF coil current, I_{coil}, could be determined as, $I_{coil} \approx U_{coil}/(\omega L_{coil})$. Thus, I_{coil} is inversely proportional to ω while coil power losses, $P_{coil} \sim I_{coil}^2$ (see Eq. (1)) are inversely proportional to f^2. This is justified by the results of calculation of P_{coil} made at two RF frequencies, $f = 3{,}4$ and $5{,}1$ MHz, for induction lamps with identical lamp parameters (Figs. 2,3).

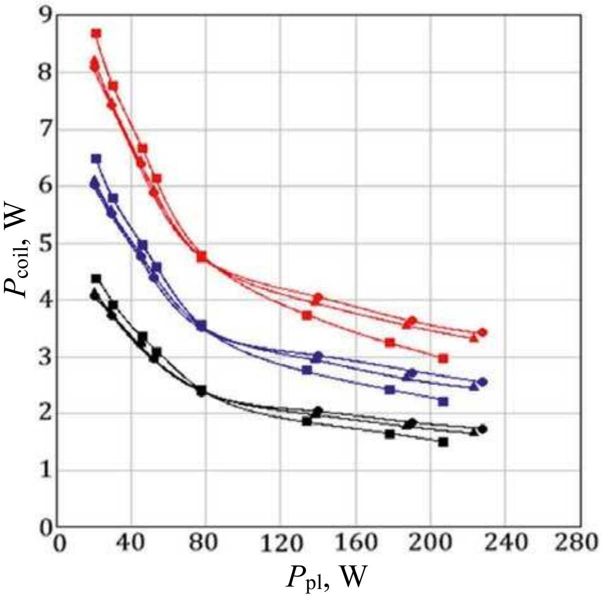

Fig. 4. Dependence of P_{coil} on P_{pl}; d_t = 25mm; N: 3 (red), 4 (blue), 6 (black); p_{Ar}, mmHg: ● – 0.1; ▲– 0.3; ■ – 1.0; f = 3.4MHz

It can be also seen from Figs. 2 and 3 that at relatively high values of P_{pl} in the lamp with d_t = 38 mm, P_{coil} could be higher than that in the lamp with d_t = 25mm. The higher f, the lower value of P_{pl} at which the curves P_{coil} (P_{pl}) calculated for lamps with different diameter "cross".

In low temperature low pressure (LP) plasmas, the increase of plasma power (actually, plasma electron density, n_e) causes the transition of ionization mechanism from electron-atom single collision to two-step ionisation process and, hence, to reduction of RF electric field in plasma, E_{pl} [4]. In non-ferrite LP induction discharges excited with the help of induction coil at frequencies of $\omega << \nu_e$, lowering of $\bar{E}_{pl}$ causes in accordance with (7) and (8) the decrease of P_{coil}.

Reducing lamp tube diameter, d_t, from 16 mm to 25mm leads to the decrease of plasma electric field, $\bar{E}_{pl}$, [2, 9] that in its turn causes significantly, in accordance with (8), decrease coil power losses, P_{coil} (Figs. 2 and 3) and k (due to the increase of S_{pl}) but results in the increase of Λ_{pl} and Q_{pl}. As it follows from (8) and is shown in Figs. 2 and 3, the dependence of P_{coil} on d_t turn out to be very complex and has its minimum at relatively high values of P_{pl} and f.

Increase of buffer gas (argon) pressure from 0.1 to 1.0 mmHg causes insignificant decrease of E_{pl} [9] and, in accordance with (7) and (8), slight decrease of P_{coil} (Figs. 2 and 3).

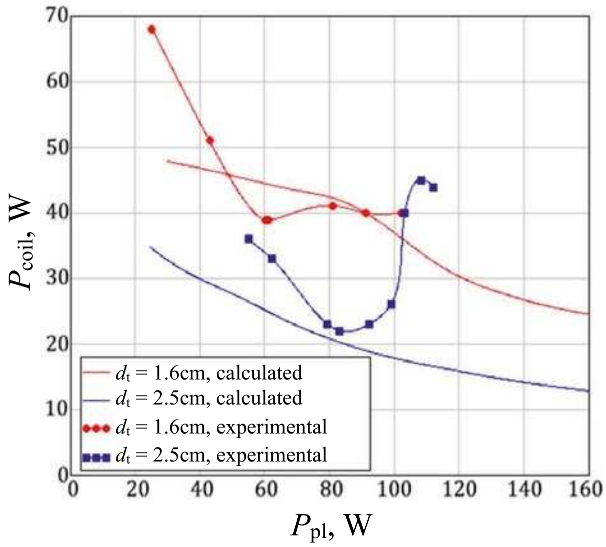

Fig. 5. Dependence of P_{coil} on P_{pl}; d_t = 16mm and 25mm; p_{Ar} = 1.0mmHg; N = 3; f = 1.7MHz

Increase of P_{pl} (and, therefore, I_{pl} and n_e) is accompanied by the decrease of R_{pl}, that (with a reasonable assumption of independence of L_{ind} on I_{pl}) causes the growth of plasma quality factor, Q_{pl} (= $\omega L_{ind}/R_{pl}$). At low values of P_{pl}, when R_{pl} is high, plasma quality factor, Q_{pl}, is very low (<0.1) and in accordance with (7) and (8) does not affect P_{coil}. The further increase of P_{pl} and d_t causes the decrease of R_{pl} and, hence, the growth of Q_{pl} that increasingly affects P_{coil} and the character of the dependence of P_{coil} on P_{pl} that changes from "negative" to positive" one forming the minimum at $P_{pl, min}$ (Fig. 3). Similar dependences of P_{coil} on P_{pl}, with the their minimums shifted with increase of f and d_t to lower values of P_{pl}, were experimentally observed in linear ferrite-free electrode-less lamps excited with the help of induction coil at f = 6–12 MHz [10].

The effect of the number of coil turns, N, on coil power losses, P_{coil}, is shown in Fig. 4. It is seen that in accordance with (8), P_{coil} is inversely proportional to N.

5. COMPARISON OF CALCULATION RESULTS WITH THE EXPERIMENT

The experimental data of P_{coil} measured in two inductive lamps with tube diameter 16 and 25 mm excited at RF frequency of 1,7 MHz are presented in Fig. 5 as functions of P_{pl}. The dependencies of P_{coil} on P_{pl} calculated for the same lamps are plotted in Fig. 5. It is seen that the experimental dependence

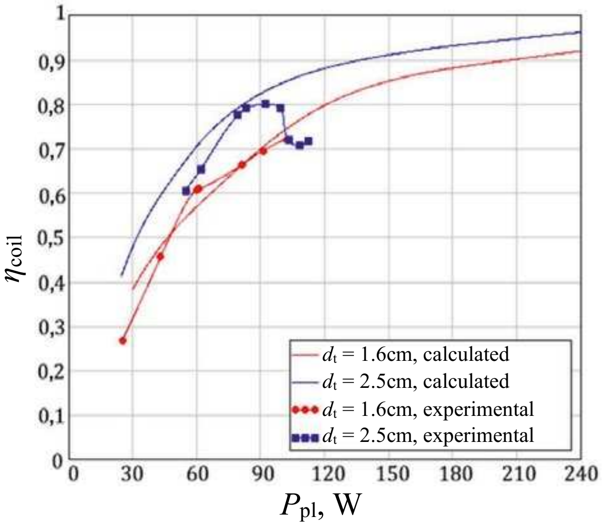

Fig. 6. Dependence of RF inductor (coil) power efficiency, η_{coil}, on P_{pl}. d_t = 16 mm and 25 mm; p_{Ar} = 1.0 mmHg; N = 3; f = 1.7MHz

of P_{coil} on P_{pl} of the lamp with smaller tube diameter (16 mm) has shallow minimum at $P_{pl,\,min}$= 60W while the experimental dependence of P_{coil} on P_{pl} of the lamp with larger tube diameter (25 mm) has deep minimum at $P_{pl,\,min}$ = 85W. It should be noted that the calculated values of P_{coil} of the lamp with d_t = 16 mm are in good agreement with the calculated data of P_{coil} of the lamp with the tube of larger diameter (25 mm) considerably exceed the experimental ones at $P_{pl,\,min}$ > 90 W.

It is from Fig. 5 that both minimums in dependencies $P_{coil}(P_{pl})$ are at plasma powers, $P_{pl,\,min}$, which are much smaller than those caused by coil power losses increase due to the growth of plasma quality factor, Q_{pl} > 0,3, see (8). It is believed that the minimums in Fig. 5 and further growth of P_{coil} observed in the experimental dependencies of P_{coil} on P_{pl} are related to skin effect pronounced in induction discharges at f = 1–5MHz and plasma densities, $n_e > 10^{11}$cm^{-3} [4, 10, 11].

Indeed, skin effect that "pushes" RF electric field to discharge tube walls where coil wire is located, thereby, increases $\bar{E}_{pl}$ [4, 11] and thus causes the increase P_{coil}. The observed discrepancy between calculated and experimental data seems to be caused by not taking into account skin effect in inductive discharge model.

It could be seen in Fig. 6 that in both lamps, at relatively low values of P_{pl}, η_{coil} rapidly increases with P_{pl} and at high values of P_{pl} asymptotically approaches to 1. The discrepancy between experimental and calculated dependencies of η_{coil} on P_{pl} in the lamp with d_t = 25mm observed at P_{pl} > 85W are believed to be due to non-considering skin effect in LP inductive discharge model.

6. CONCLUSION

• With the use of the transformer model, the analytic expression for induction coil power losses, P_{coil}, in LP inductively-coupled discharges excited at frequencies of $\omega << \nu_e$ in ferrite-free closed-loop tube with the mixture of mercury vapour and argon were derived.

• It was found that the dependence of P_{coil} on plasma power, P_{pl}, has the minimum that shifts to lower values of P_{pl} as the discharge tube diameter, d_t, and RF frequency, f, increase.

• It was shown that discharge tube diameter, d_t, affects coil power losses, P_{coil}, via RF electric field, plasma turn length, Λ_{pl}, and quality factor, Q_{pl}, and plasma turn and induction coil coupling coefficient, k.

• It is found that P_{coil} is inversely proportional to coil turns number, N, and slightly decreases as argon pressures grows from 0.1 mm Hg to 1.0 mm Hg.

• The results of calculation of coil power losses, P_{coil}, and coil power efficiency, Q_{coil}, made for the ferrite-free electrode-less lamp with discharge tube diameter, d_t = 16mm, were found in satisfactory qualitative agreement with the experiment. Discrepancy between calculated and experimental obtained P_{coil} and Q_{coil} in lamp with tube diameter of 25mm at $P_{pl} \geq 80$W is supposedly due to not taking into account skin effect in the transformer model of LP inductively-coupled discharge.

• The results obtained could be used for optimisation of RF frequency, induction coil number of turns, and length, and diameter of discharge closed-loop tube of ferrite-free electrode-less LP mercury UV lamps.

REFERENCES

1. Pavel V. Starshinov, Oleg A. Popov, Igor V. Irkhin, Vladimir A. Levchenko, and Vasina Victoria N. Electrodeless UV Lamp on the Basis of Low-Pressure Mercury Discharge in a Closed Non-Ferrite Tube// Light & Engineering, 2019, Vol. 27, # 6, pp. 133–136.

2. Starshinov, P.V., Popov O.A., Irkhin, I.V., Vasina, V.N., Levchenko, V.A. Electric and Radiation Characteristics of Ferrite-free Electrodeless Inductively-coupled

UV Lamps in Closed-loop Tubes [Elektricheskie i izluchatelnyiye kharakteristiki induktivnykh besferritnykh rtutnykh UF lamp v zamknutykh trubkakh] // Bulletin of MEI, 2019, #. 3, pp. 87–97.

3. Vladimir A. Levchenko, Oleg A. Popov, Sergei A. Svitnev, and Starshinov Pavel V.

Electric and Radiation Characteristics of a Transformer Type Lamp with a Discharge Tube of 16.6 mm Diameter// Light & Engineering, 2016, Vol. 24, #2, pp. 77–81.

4. Raiser, Yu.P. Physics of Gas Discharges [Fizika gazovogo razryada]. Moscow: Nauka, 1987, 591 p.

5. Piejak, R.B., Godyak, V.A., Alexandrovich, B.M. A Simple Analyses of an Inductive RF Discharge // Plasma Sources Sci.Technol. 1992, № 1, pp. 179–185.

6. Popov, O.A., Chandler, R.T. Ferrite-free High Power Electrodeless Fluorescent Lamp Operated at a Frequency of 160–1000 kHz // Plasma Sources Science and Technology, 2002, # 11, pp. 218–227.

7. Gudmundsson, J.T. and Lieberman, M.A. Magnetic Induction and Plasma Impedance in a Cylindrical Inductive Discharge// Plasma Sources Sci. Tech. 1997, Vol. 6, № 4, pp. 540–550.

8. Popov, O.A., Starshinov, P.V., Vasina, V.N. Study of Characteristics of Electrodeless Ferrite-free Low Pressure Mercury Discharge in a Closed-loop Tube [Issledovanie kharakteristik induktsionnogo besferritnogo rtutnogo razryada nizkogo davleniya v zamknutoi trubket] // Bulletin of MEI, 2018, Vol. 4, pp. 89–96.

6. Rokhlin, G.N. Discharge light sources [Razryadnyie istochniki sveta]. Moscow: Energoatomizdat, 1991, 720 p.

10. Svitnev, S.A., Popov, O.A., Levchenko, V.A., Starshinov, P.V. Characteristics of Low-Pressure Ferrite-free Induction Discharge. Part 1. Electrical Parameters of Induction Coil [Kharakteristiki besferritnogo induktsionnogo razryada nizkogo davleniya. Chast 1. Elektricheskiye parametry katushki] // Uspekhi prikladnoi fiziki, 2016, Vol. 2, pp. 139–149.

11. Nikiforova, V.A., Popov, O.A. Effect of RF Field Frequency and Discharge Current on Radial Distribution of Parameters of Plasma of Ferrite-free Inductively-coupled Discharge in Closed-loop Tube [Vliyanie chastoty VCh polya i razryadnogo toka na radialnoye raspredeleniye parameterov plazmy induktsionnogo besferritnogo razryada v zamknutoi trubke] // Bulletin of MEI, 2012, Vol. 1, pp. 108–114.

Ekaterina V. Lovlya,
student of the Light Engineering department,
NIU MEI

Oleg A. Popov,
Prof., Doctor of Technical Sciences, graduated from Moscow Power Engineering Institute (MEI) in 1965. Currently, he is a Professor of Light Engineering department, NIU MEI, Member of the Russian Academy of Electric Engineering