East European Journal of Physics. **2.** 85-90 (2022)
DOI:10.26565/2312-4334-2022-2-10 ISSN 2312-4334

INVESTIGATION OF A GLOW DISCHARGE WITH A COAXIAL HOLLOW CATHODE†

Stanislav V. Pogorelov[a], **Volodymyr A. Timaniuk**[a,*], **Ihor V. Krasovskyi**[a], **Nikolay G. Kokodii**[b]

[a]*National University of Pharmacy, Kharkiv, Ukraine*
[b]*V.N. Karazin Kharkiv National University, Kharkiv, Ukraine*
**Corresponding Author: vladimir.timaniuk@gmail.com, tel.: +38 095 505 39 19*
Received February 11, 2022; revised March 26, 2022; accepted April 4, 2022

The article is devoted to the study of the operating modes of a glow discharge with a coaxial hollow cathode in helium and neon gases. It is shown that the burning voltage of a discharge with a coaxial hollow cathode is lower than one with a cylindrical hollow cathode of equal diameter, and the position of the optimal pressure range depends on the width of the annular gap of the cavity. It is noted that the rod current density is 3-5 times higher than the cylinder current density. The insignificant role of the photoelectric effect in the processes of electron emission from the cathode is proved. It is shown that the intensity of the atomic spectral lines of the cathode material increases significantly when a coaxial hollow cathode is used.
Keywords: glow discharge, hollow cathode, cathode configuration, spectral sources, electron oscillations, discharge current density.
PACS: 52.80.Pi; 52.80.Tn

The vast majority of glow discharge studies in hollow cathode devices use cylindrical hollow cathodes that are open at one or both ends. However, the effect of a hollow cathode is also observed with other configuration of the cathode cavity (a double hollow cathode formed by two flat plates located at a rather small distance; or hollow cathodes with different shapes of the inner cavity [1]), as long as conditions for the oscillation of fast electrons in the cross section of the cathode cavity are provided. These designs have no advantages over the cylindrical hollow cathode and therefore have not gained widespread acceptance. An exception is the slit hollow cathode used in ion lasers, which is essentially a cylindrical hollow cathode, with withdrawal of a current through a slit in the side surface of the cylinder.

GOALS OF ARTICLE

Analyzing the features of the discharge mechanism with a cylindrical hollow cathode, the following drawback of these cathodes can be noted [2, 3, 4]. On the axis of the cathode cavity, there is a maximum concentration of slow electrons, which have an energy of less than 1 eV near the upper boundary of the optimal pressures range. Consequently, in the axial region of the cylindrical cathode cavity, conditions for intense volume recombination of electrons and ions are created, because of this recombination the degree of plasma ionization in the cathode cavity decreases. Placement of additional electrodes in the cathode cavity, for example, an anode or an insulated electrode [3] leads to the loss of fast electrons due to violation of the conditions for the oscillation of fast electrons and a sharp increase in the burning voltage of the discharge. However, placing a metal rod, connected to the cathode, on the axis of the cathode cavity leads to a decrease in the burning voltage of the discharge in comparison with a hollow cathode formed by the same cylinder without a rod. Therefore, such a hollow cathode, called coaxial, was investigated in more detail.

MATERIALS AND METHODS

One of the designs of discharge tubes with a coaxial hollow cathode is shown in Figure 1.

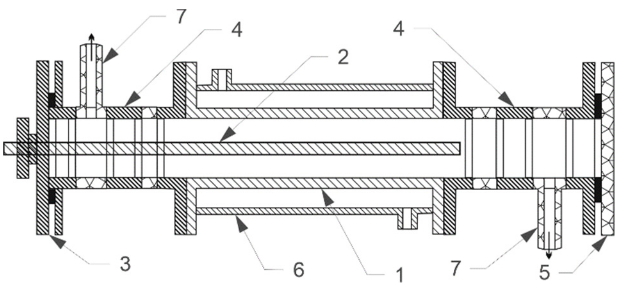

Figure 1. Construction of the discharge tube with a coaxial hollow cathode: 1 - cylinder; 2 - removable rod; 3 - side flange; 4 - anodes; 5 – glass plate; 6 – water cooling jacket; 7 – glass pipes for gas.

The cathode cavity is formed by a cylinder 1 and a removable rod of various diameters 2, fixed with a vitrified holder in the side flange 3. The anodes are two annular electrodes 4 located coaxially with the cathode cavity. The second side flange is covered with a glass plate 5 for visual observation and output of optical radiation from the cathode cavity. The outer

† *Cite as*: S.V. Pogorelov, V.A. Timaniuk, I.V. Krasovskyi, and N.G. Kokodii, East Eur. J. Phys. **2**, 85 (2022), https://doi.org/10.26565/2312-4334-2022-2-10

cylinder is equipped with a water cooling jacket 6, filling the tube with gas and pumping out was performed through glass pipes 7. The rod could be introduced into the cathode cavity using a bellows system that allows the rod to be shifted parallel to the axis of the cathode cavity. All measurements were carried out in the continuous flow regime of spectrally pure helium and neon gases.

RESULTS

For a cylindrical hollow cathode, the discharge burning voltage depends on the geometric dimensions of the cathode cavity and the cathode material. Figure 2 shows the dependences of the burning voltage on the helium pressure for a coaxial hollow cathode with a rod diameter of 2 mm and 5 mm at a discharge current of 10 mA. Similar measurements were also carried out for the cylindrical hollow cathode.

It can be seen that, in the region of optimal pressures, the burning voltage in the coaxial hollow cathode is lower than in the cylindrical one, and a shift of both boundaries of the region of optimal pressures is observed. With an increase in the diameter of the rod, the transverse size of the resulting annular cavity, along which the electron oscillations occur, decreases. And just like for a cylindrical hollow cathode, with a decrease in the diameter, the burning voltage decreases and the boundaries of the region of optimal pressures shift towards higher pressures.

Figure 3 shows the dependence of the burning voltage on the helium pressure for a cylindrical hollow cathode and coaxial hollow cathode formed by an aluminum cylinder with a diameter of 30 mm and a rod with a diameter of 5 mm made of molybdenum, aluminum and nickel.

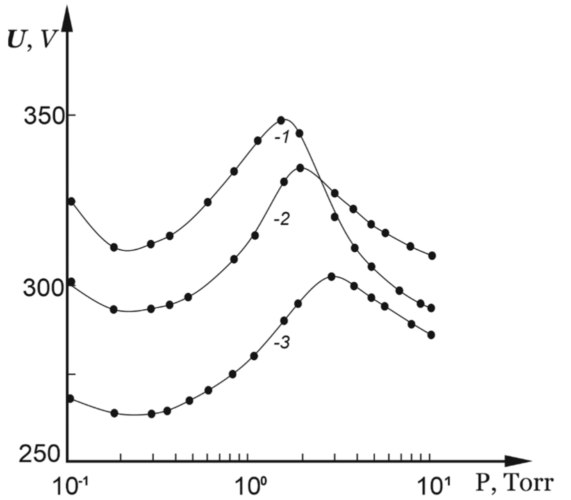

Figure 2. The dependences of the burning voltage on the helium pressure for a cylindrical hollow cathode (CylHC) with a cylinder diameter of 30 mm (1) and for a coaxial hollow cathode (CoaxHC) with a rod diameter of 2 mm (2) and 5 mm (3)

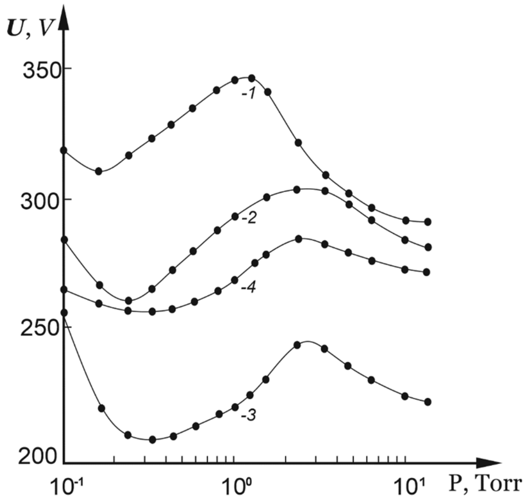

Figure 3. The dependence of the burning voltage on the helium pressure for CylHC with a cylinder diameter of 30 mm (1) and CoaxHC with a rod diameter of 5 mm of molybdenum (2), aluminum (3) and nickel (4)

Curve 1 corresponds to a hollow cathode without a rod. It can be seen that the burning voltage of the discharge depends on the material of the rod and also it depends on the material of a cylindrical hollow cathode. If both the outer cylinder and the rod are made of nickel (Figure 4), then the burning voltage at the minimum of the U(P) dependence is 116 V, which is less than the normal cathode potential drop for a nickel-helium pair (144V) [5].

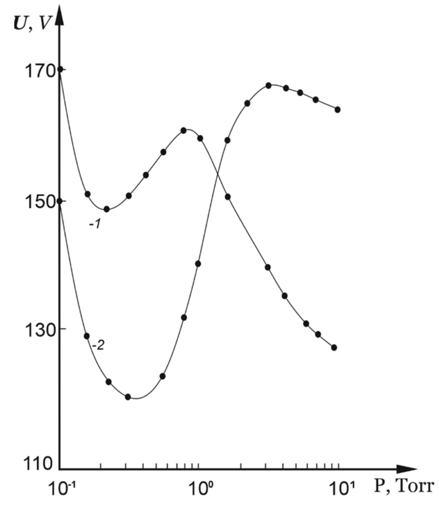

Figure 4. The dependence of the burning voltage on the neon (1) and helium (2) pressure for CoaxHC with a nickel cylinder diameter of 30 mm and a nickel rod diameter of 10 mm at the discharge current of 100 mA

The fact that the burning voltage in the coaxial hollow cathode depends on the rod material indicates that the atomized atoms of the outer cylinder fall on the rod in an insignificant amount. The displacement of the boundaries of the optimal pressures region depending on the type of gas for a coaxial hollow cathode has the same regularities as for a cylindrical one. One would expect that if the width of the annular gap of the coaxial hollow cathode is equal to the diameter of the cylindrical hollow cathode, the regions of optimal pressures should coincide. Comparison for helium gas of the upper PU and lower PL boundaries of the optimal pressures region for a coaxial hollow cathode (CoaxHC) and cylindrical (CylHC) with the equality of the gap width and the diameter of the cathode cavity is given in Table.

Table. The value of the upper P_U and lower P_L boundaries of the optimal pressures region at the same values of the width of the gap of the CoaxHC and the diameter of the CylHC.

	6.5 mm		10 mm		12.5 mm		14 mm	
	CoaxHC	CylHC	CoaxHC	CylHC	CoaxHC	CylHC	CoaxHC	CylHC
P_U, Torr	5.0	7.5	3.0	4.5	3.0	4.0	2.0	3.5
P_L, Torr	0.6	1.5	0.4	0.9	0.4	0.75	0.3	0.7
P_U/P_L	8.3	5.0	7.5	5.0	7.5	5.0	6,7	5.0

DISCUSSIONS

It can be seen from the table that in all cases the region of optimal pressures of the coaxial hollow cathode is shifted relative to the cylindrical one towards lower pressures. At the same time, the value of PU/PL for a coaxial hollow cathode is higher than for a cylindrical one. All this indicates that the oscillations of fast electrons in the coaxial hollow cathode occur not only in the radial direction. Part of the electrons emerging from the outer cylinder is decelerated in the dark cathode space near the rod, and part of the electrons first bends around this region and then falls into the dark cathode space near the cylinder again. Thus, the length of the trajectory for different electrons a lies in the range from S - the width of the annular gap to D - the diameter of the outer cylinder. As a result, the width of the optimal pressure region increases. The above considerations are confirmed by the fact that when the rod is displaced relative to the axis of the outer cylinder, the region of optimal pressures also expands.

The problem of studying the distribution of the current in a coaxial hollow cathode has two aspects. First, the distribution of the current between the outer cylinder and the rod, and second, the distribution of the current along the length of the cathode cavity [6]. In all discharge tubes, the rod had an insulated terminal, and this made it possible to measure the rod current and its dependence on various conditions. A tube with a sectioned hollow cathode was used to measure the longitudinal distribution of the current.

It turned out that the current to the rod makes up a significant part of the total cathode current and is practically independent of the gas pressure in the region of optimal pressures. Figure 5 shows the dependence of the current on the helium gas pressure for a coaxial nickel cathode with an outer cylinder 30 mm in diameter and different rod diameters: 1 mm, 2.5 mm, 5 mm and 10 mm and the same discharge current of 100 mA.

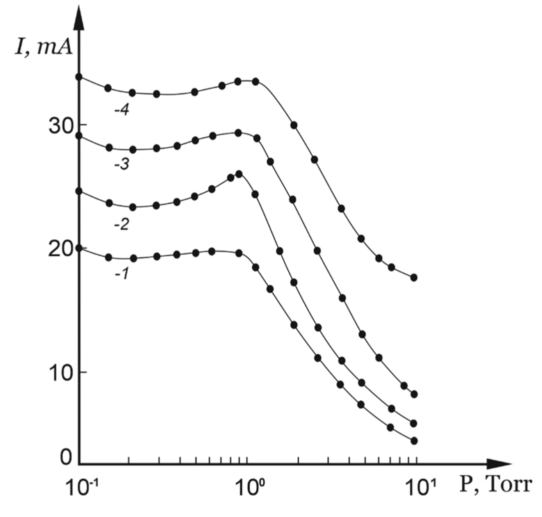

Figure 5. The dependence of the current to the rod on the helium pressure for a nickel CoaxHC with a cylinder diameter of 30 mm and rod diameters of 1 mm (1), 2.5 mm (2), 5 mm (3) and 10 mm (4) at the discharge current of 100 mA

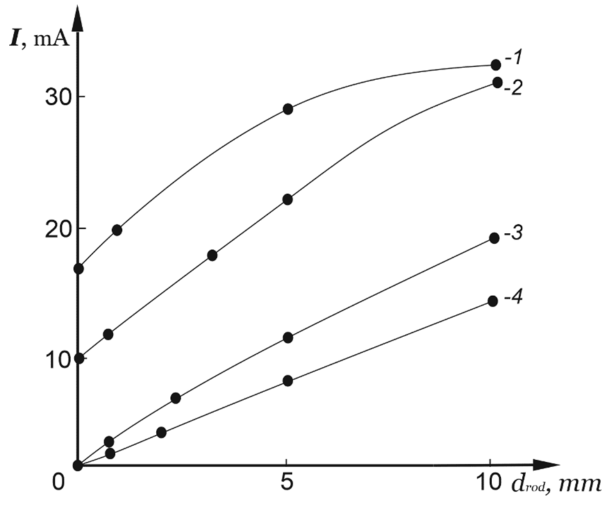

Figure 6. The dependence of the current to the rod on its diameter at helium pressure of 1Torr (1), 2 Torr (2), 5 Torr (3), 10 Torr (4) at the discharge current of 100 mA. Cylinder diameter equals 30 mm

With an increase in the diameter of the rod, the transition point from a flat section to a steeply dipping one shifts towards high pressures. With the smallest diameter of the rod (1 mm), the rod current in the pressure range of 0.1-1 Torr is about 20% of the total discharge current, although the surface of the rod in this case is 30 times smaller than the surface of the cylinder. Figure 6 shows the dependence of the rod current on its diameter at various helium pressures.

Curve 1 corresponds to the pressure range from 0.1 to 1 Torr. At these pressures, an increase in the diameter of the rod by a factor of 10 leads to an insignificant increase in its current (from 20 mA to 32 mA). With increasing pressure, the dependence of the rod current on the diameter increases, and at a pressure of 10 Torr, the rod current is proportional to its diameter. Such a nature of the curves may indicate a change in the mechanism of emission from the cathode in the studied pressure range.

When the rod is displaced parallel to the axis of the cathode cavity, the pattern of the dependence of the current to the rod on the gas pressure changes. Figure 7 shows the dependence of the current to the rod on the helium pressure for the rod located on the axis of the cavity (curve 1) and when the rod is displaced from the axis by 5 mm (2) and 10 mm (3).

When the rod is displaced perpendicular to the axis, a clear maximum appears on the curves, which, with an increase in the displacement of the rod, shifts to the region of higher pressures. At low gas pressures, the rod current decreases, at high gas pressures, it increases. This behavior of the curves indicates that the current to the rod is determined by the plasma concentration in the cavity of the cylindrical hollow cathode at the location of the rod.

Figure 8 shows the dependences of the current density to the rod on the helium pressure for rods of different diameters, as well as the dependences of the current density to the cylinder.

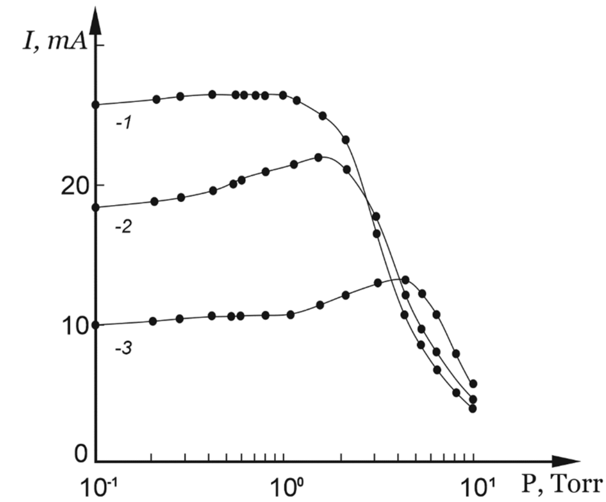

Figure 7. The dependence of the current to the rod on the helium pressure for the rod located on the axis (1) and the rod displaced from the axis by $\Delta_r = 5mm$ (2) and $\Delta_r = 10mm$ (3) at the discharge current of 100 mA. Cylinder diameter equals 30 mm. Rod diameter equals 2 mm

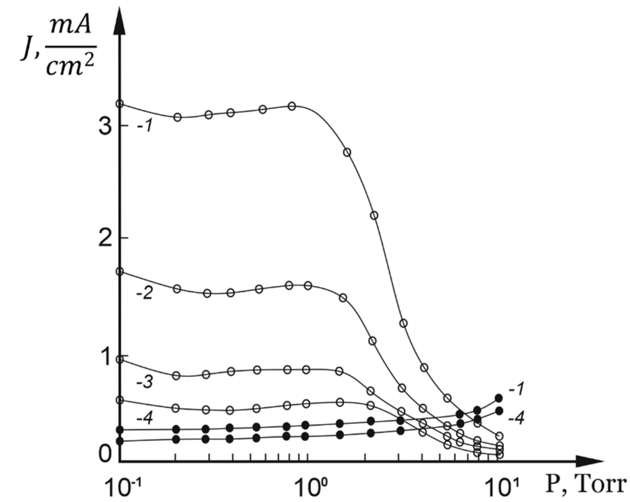

Figure 8. The dependences of the current density to the rod (-○-) and to the cylinder (-●-) on the helium pressure with a cylinder diameter of 30 mm and rod diameters of 1 mm (1), 2.5 mm (2), 5 mm (3) and 10 mm (4) at the discharge current of 100 mA

The current density to the rod increases sharply with decreasing rod diameter, while the current density to the cylinder remains almost unchanged. With an increase in the gas pressure, the current density to the rod decreases and at a pressure above 5 Torr it becomes less than the current density to the cylinder.

The current distribution along the cylinder of a coaxial hollow cathode was studied using a tube with a sectioned hollow cathode 15 mm in diameter, on the axis of which a rod 1 mm and 2 mm in diameter was located. The pattern of the dependence of the current along the length of the coaxial hollow cathode turned out to be qualitatively the same as for the cylindrical hollow cathode. When the rod is placed on the axis of the cylinder, the transverse dimension of the cathode cavity decreases, which prevents the penetration of plasma into the depth of the cathode. Therefore, in order to provide a relatively uniform current load of the cylinder in the coaxial hollow cathode, its length in comparison with the cylindrical one must be reduced in proportion to the decrease in the transverse size of the cathode cavity [7].

Taking into account the fact that in a coaxial hollow cathode the rod current density can be much higher than the cylinder one, it can be assumed that the rod material will be sputtered more intensively than the cylinder material, and the lines of the rod material will prevail in the spectrum of the discharge glow. These considerations stimulated spectral studies of the radiation from a discharge with a coaxial hollow cathode. Copper and iron were used as the rod materials. Measurements were carried out with a discharge in helium and neon. The emission spectrum was recorded using an ISP-51 spectrograph.

The region of negative glow in a discharge with a coaxial hollow cathode has the shape of a ring and changes in the same way as in a discharge with a cylindrical hollow cathode. A dark cathode space exists near the surface of the cylinder and near the surface of the rod. With increasing gas pressure, the width of the dark cathode space decreases, and at pressures less than 2 Torr, the negative glow is distributed into two parts: brighter and wider is near the cylinder, less bright and narrow is near the rod. Photographing the discharge glow with subsequent photometry of the film on the MF-2 microphotometer made it possible to measure the width of the dark cathode space in the discharge (d_c). The value of d_c near the surface of the rod turns out to be constant up to a pressure of 1 Torr, moreover, d_c near the rod is almost 2 times less than near the cylinder. This is due to the fact that the cathode potential drop at the rod and at the cylinder is the same, but the rod current density in this case is 3.4 times higher than the cylinder one. As expected, due to the fact that the current density to the rod is higher than to the cylinder, in the emission spectrum of the coaxial hollow cathode, mainly the lines of the rod material are observed.

When the rod is connected, additional lines appear in the spectrum, the identification of which showed that these are analytical lines of iron at 404.5 nm, 427.1 nm, and 438.3 nm. [8]. Thus, at a discharge current of 50 mA, the sputtering of the cylinder is still insufficient for the lines of the metal from which it is made to appear in the spectrum. When the rod is connected, despite the fact that the current to it is only 14% of the total discharge current, rather intense metal lines appear in the discharge spectrum [9]. Figure 9 shows the dependence of the intensity of three sensitive lines of iron on the discharge current at the neon gas pressure of 1 Torr.

Curves 1 — 3 were obtained for a coaxial hollow cathode; 1'— 3' for a cylindrical hollow cathode with a diameter equal to the diameter of the cylinder of the coaxial hollow cathode. It can be seen that in the coaxial hollow cathode, iron lines are reliably recorded at a discharge current of 20 mA, in a cylindrical one, a current of more than 60 mA is required. Thus, a coaxial hollow cathode is approximately 3 times more efficient than a cylindrical one for use as a source of the iron spectrum. The dependence of the intensity of the spectral lines of copper on the neon pressure for a coaxial hollow cathode is shown in Figure 10.

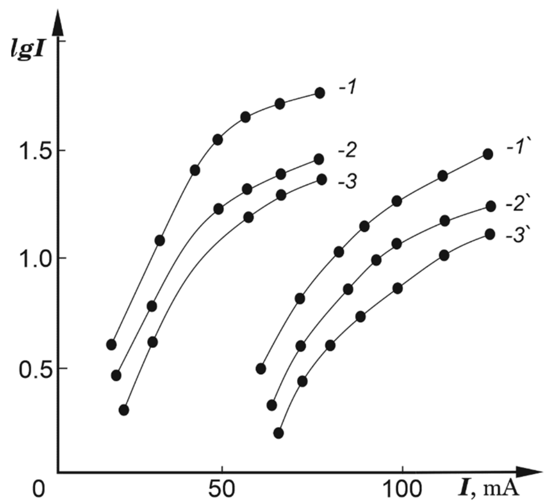

Figure 9. The dependence of the intensity of three sensitive lines of iron λ=438.3 nm (1), λ=427.2 nm (2) and λ=404.6 nm (3) on the discharge current at the neon gas pressure of 1 Torr. 1 - 3 are for CoaxHC, and 1' — 3' are for CylHC

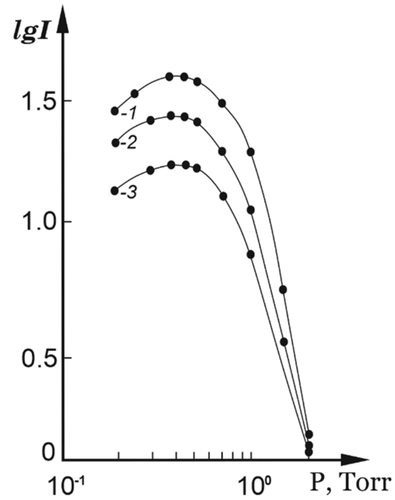

Figure 10. The dependence of the intensity of the spectral lines of copper λ=511.8 nm (1), λ=515.3 nm (2) and λ=510.5 nm (3) on the neon pressure for CoaxHC at the discharge current of 20 mA

In the range of neon pressures of 0.2 - 0.8 Torr, the intensity of the spectral lines of the rod material changes little, and at higher pressures, the intensity decreases sharply. This behavior of the curves is due to the action of several factors. At low gas pressures, the supply of sputtered atoms to the glow region increases, but the concentration of electrons in the plasma decreases, and as a result, the dependence of the radiation intensity on the gas pressure is weakened. As the pressure rises above 1 Torr, the number of sputtered atoms, the plasma concentration, and the current density to the rod decrease. This leads to a sharp decrease in the radiation intensity of the spectral lines of the rod material. Similar measurements were carried out for a discharge with a coaxial hollow cathode in helium. Due to the low mass of the ion, the sputtering of atoms of the cathode material and the intensity of the corresponding spectral lines in helium are lower than in neon.

CONCLUSIONS

As a result of studying the main electrical and spectral characteristics of a discharge with a coaxial hollow cathode made of various materials for different diameters of the outer cylinder and rod, the following new results were obtained.

1. In the annular cavity formed by electrically connected coaxial electrodes, the "hollow cathode effect" is preserved. The burning voltage of a discharge with a coaxial hollow cathode in the region of optimal pressures is lower than that of a discharge with a cylindrical cathode of the same diameter.

2. The position of the region of optimal pressures of the coaxial hollow cathode depends on the width of the annular gap of the cavity and the type of gas. The width of the region of optimal pressures of a coaxial hollow cathode is wider than that of a cylindrical one with an equal transverse size of the cathode cavity. The dependence of the discharge burning voltage on the gas pressure in a coaxial hollow cathode is weaker than in a cylindrical one.

3. The rod current density is 3-5 times higher than the cylinder current density and at low pressures is practically independent of the pressure and the gas type.

4. The weak dependence of the current to the rod on its diameter indicates an insignificant role of the photoelectric effect in the processes of electron emission from the cathode.

5. Due to the higher current density to the rod, the width of the dark cathode space near the rod surface is approximately 2 times less than that near the cylinder surface.

6. In the spectrum of a discharge with a coaxial hollow cathode, the intensity of the lines of the rod material sputtered atoms is much higher than that of the atoms of the cylinder material.

ORCID IDs

Stanislav V. Pogorelov, https://orcid.org/0000-0002-0189-8655; **Volodymyr A. Timaniuk**, https://orcid.org/0000-0003-0689-6074
Ihor V. Krasovskyi, https://orcid.org/0000-0003-4585-7377; **Nikolay G. Kokodii**, https://orcid.org/0000-0003-1325-4563

REFERENCES

[1] A.S. Klimov, Yu.A. Burachevsky and I.S. Zhirkov, Proceedings of TUSUR University, **18**(2), 53 (2008), https://journal.tusur.ru/storage/47466/53-58.pdf?1467799502. (in Russian)
[2] B.I. Moskalev, *Разряд с полым катодом* [*Hollow cathode discharge*], (Energiya, Moscow, 1969), pp. 184. (in Russian)
[3] V.A. Timanyuk, N.G. Kokodiy, and F.G. Diaghileva, Papers SWORLD Transport, Engineering, Physics and Mathematics, **2**(46), 95 (2017), https://www.sworld.com.ua/ntsw/117-2.pdf. (in Russian)
[4] V. Lisovskiy, and I. Bogodielnyi, East European Journal of Physics, **1025**(4), 43 (2012), https://periodicals.karazin.ua/eejp/article/view/13588
[5] P.N. Chistyakov, in: *Физическая электроника: сборник статей* [*Physical electronics: collection of articles*], (Atomizdat, Moscow, 1966), pp. 3-19. (in Russian)
[6] Bánó, G., Szalai, L., Kutasi, K. et al. Operation characteristics of the Au-II 690-nm laser transition in a segmented hollow-cathode discharge. Appl Phys B, **70**, 521 (2000), https://doi.org/10.1007/s003400050855.
[7] S.V. Pogorelov, V.A. Timaniuk, N.G. Kokodii, and I.V. Krasovskyi, East European Journal of Physics, **(2)**, 155 (2021), https://doi.org/10.26565/2312-4334-2021-2-13.
[8] A.N. Zaidel et al, *Таблицы спектральных линий* [*Spectral Lines Tables*], (Nauka, Moscow, 1977), pp. 798. (in Russian)
[9] V.H. Baggio-Scheid, J.W. Neri, and G. de Vasconcelos, Surface and Coatings Technology, **146-147**, 469-473 (2001), https://doi.org/10.1016/S0257-8972(01)01458-X.

ДОСЛІДЖЕННЯ ТЛІЮЧОГО РОЗРЯДУ З КОАКСІАЛЬНИМ ПОРОЖНИСТИМ КАТОДОМ

Станіслав В. Погорєлов[а], Володимир О. Тіманюк[а], Ігор В. Красовський[а], Микола Г. Кокодій[б]
[а]*Національний фармацевтичний університет, Харків, Україна*
[б]*Харківський національний університет імені В. Н. Каразіна, Харків, Україна*

Стаття присвячена дослідженню режимів роботи тліючого розряду з коаксіальним порожнистим катодом у газах гелію та неону. Показано, що напруга горіння розряду з коаксіальним порожнистим катодом нижча, ніж з циліндричним порожнистим катодом однакового діаметра, а положення оптимального діапазону тиску залежить від ширини кільцевого зазору порожнини. Зазначено, що щільність струму штока в 3-5 разів перевищує щільність струму циліндра. Доведено незначну роль фотоефекту в процесах емісії електронів з катода. Показано, що при використанні коаксіального порожнистого катода інтенсивність атомних спектральних ліній матеріалу катода значно зростає.

Ключові слова: тліючий розряд, порожнистий катод, конфігурація катода, спектральні джерела, електронні коливання, щільність струму розряду.