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EVALUATION OF THE THERMAL REGIME OF THE CATHODE OPERATION OF A HIGH-VOLTAGE GLOW DISCHARGE ELECTRON GUN, WHICH FORMS A RIBBON ELECTRON BEAM

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Abstract. The article discusses the various methods of estimating the surface cathode temperature of the high-voltage glow discharge electron gun, which forms a ribbon electron beam with a linear focus. Numerical estimations have been made to design the cathode assembly of an industrial gun. It is shown that the most effective way to make approximate estimates of the temperature of the cathode surface in high-voltage glow discharge electron guns for various technological purposes is to use arithmetic-logical ratios for modeling the geometry of the cathode assembly and locus functions for estimating the temperature distribution. The accuracy of such estimates, made using the heat balance equation, was 5–10%, sufficient at the initial stage of designing an electron gun. It is shown that using the SolidWorks CAD software complex for designing high-voltage glow discharge electron guns is effective only for solving the complex engineering design tasks and preparing the corresponding technical documentation. The results of the theoretical research published in the article are of interest to a wide range of specialists engaged in developing electron beam equipment and its implementation in industrial production.

Keywords: electron gun, high-voltage glow discharge, CAD-systems, thermodynamic equation, heat balance equation, arithmetic-logical relation, locus.

INTRODUCTION

Today, high-voltage glow discharge (HVGD) electron guns are widely used in various branches of industry [1–3]. The main fields of application of such electron guns are electron-beam welding of thin-walled parts and their assemblies, deposition of ceramic coatings in an environment of active or inert gases, depending on the requirements of the technological process, as well as electron-beam cleaning of refractory metals and ceramic materials for the further use of high-refining materials in modern production technologies. The main advantages of HVGD electron guns over traditional electron sources with incandescent cathodes are the following [1–3].

1. Stability and reliability of operation in conditions of low vacuum in the environment of various gases, in particular inert and active ones.

2. Simplicity of the design of HVGD electron guns with the possibility of replacing spent units, in particular the cold cathode of the HVGD.

3. Simplicity of vacuum technological equipment, without the need to ensure the operation of the electron gun in conditions of high vacuum.

4. Simple control of the power of the electron beam. In general, there are two ways to provide such control in order to improve the quality of industrial products that are subject to heat treatment with an electron beam. There are the following: changing the pressure in the discharge gap [4] or changing the concentration of ions in the anode plasma due to the lighting of the additional auxiliary discharge [5].

In connection with the physical features of the operation of HVGD electron guns listed above and the existing advantages of these types of guns over traditional electron sources with incandescent cathodes as well as over other beam technologies, including laser ones [2; 3], the main industrial areas of application of HVGD electron guns in modern electron beam technologies are the following.

1. High-speed electron beam welding of capsules and contacts of modern electronic devices, in particular cryogenic ones [6; 7].

2. Production of ceramic films for high-quality and durable capacitors with the aim of creating a new component base of the modern electronic industry [8–11].

3. Production of ceramic films for receiving and transmitting antennas of modern microwave communication electronic means [8–11].

4. Deposition of heat-resistant and heat-protective coatings in the modern automotive, aviation, and space industries. For example, advanced modern technologies are the application of heat-protective coatings on the blades and other parts of automobile and aircraft engines [12–15].

5. Electron beam refining of refractory metals and ceramic materials in order to increase their purity and quality [16–20]. For example, in works [17–20], the features of applying electron-beam remelting technologies to obtain pure polycrystalline silicon were considered. The aim of this advanced electron-beam technology is to improve the manufacturing technology of modern semiconductor electronics devices, in particular, electronic microcircuits.

6. The modern technologies of three-dimensional printing on the metal's substrates [21].

STATEMENT OF THE PROBLEM

One of the features of the HVGD electron gun is a rather low current density from the metallic surface of the cold cathode, the maximum value of which is about $10^3 \frac{A}{m^2}$. In connection with this, an advanced direction for the introduction of HVGD electron guns in modern electron-beam technologies is the formation of profiled electron beams with a linear and circular focus from a large cathode surface. The main advantage of using such types of HVGD electron guns in modern electron-beam welding and surface treatment technologies is the extremely high productivity of the technological process, since the use of profiled electron beams allows for a short period of time to process the products of a long duration with complex geometry without the need to provide the additional scanning of the electron beam on the surface of detail, which is treated [2; 3].

The main advantages of HVGD electron guns, which form profile electron beams, are the following [2; 3].

1. A wide range of power, from 10 kW to 600 kW, which allows designing optimal equipment for a specific technological application.

2. Stability of operation in a wide vacuum range, the partial gas pressure can be from 10–4 to 10–1 Pa, including in conditions of dynamic pressure changes in the process chamber.

3. The use of different active and noble gases, as well as mixtures of them, is also possible.

4. The HVGD electron guns are compact and light in weight.

5. The HVGD electron guns are simple to exploit and repair, and they are also reliable in operation.

6. The cold cathodes of HVGD electron guns have a significant time of operation without necessary cleaning, up to 100 amps for hours or more.

The construction diagram of the electrode system of the HVGD electron gun, which forms an electron beam with a linear focus, is shown in Fig. 1. The main features of the electrode systems of HVGD electron guns, which form electron beams with a ring and linear focus, as well as methods of evaluating their geometric design parameters, were considered in papers [22–24].

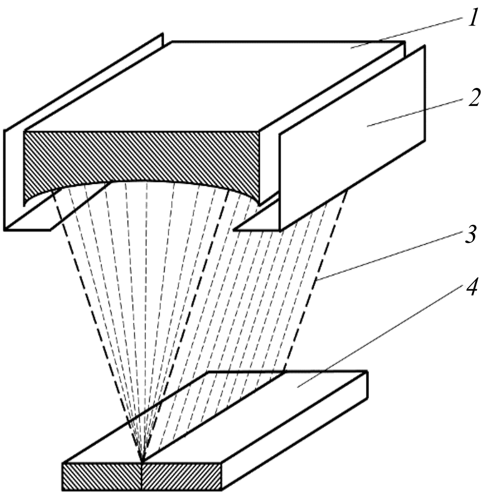


Fig. 1. Structural diagram of the HVGD electrode system, which forms an electron beam with a linear focus: *1* — cathode; *2* — anode; *3* — electron beam; *4* — product being processed

In connection with this, the most important tasks related to the mathematical model of HVGD electron sources, from a practical point of view, are estimates of the thermal modes of operation of the cold cathode, which form electron beams with a linear focus. In general, from the point of view of HVGD physics, the thermal mode of operation of the cold cathode significantly affects its emission properties [1].

Methods of analysis of the self-aligned electron-ion optics of HVGD, taking into account the assessment of the position of the plasma boundary relative to the cathode, have been studied quite thoroughly and were described in the papers [1, 25–27]. Generally, anode plasma in HVGD electrode systems is considered a moving electrode with a given potential that is transparent to electrons. The peculiarities of estimating the position of the plasma boundary in HVGD electrode systems, which form electron beams with a linear and circular focus, were considered in a paper [20]. The general theoretical approach to estimating the operating temperature of the cold cathodes of the HVGD electron guns was considered in [28].

Another approach to simulation and experimental study of the properties of powerful and intensive electron beams in vacuum and plasma devices, including microwave ones, is presented in the papers [29–31]. In the paper [29], the radiation of plasma diodes in the microwave range has been studied experimentally. In the paper [30] the penetration of an intensive electron beam into an irradiated object in dependence on the incidence angle of the electron beam has been studied. In the paper [31] model of an electron beam for an advanced method of computational dosimetry for radiation processing has been elaborated and tested.

Therefore, the main goal of this work is to evaluate the thermal modes of operation of the cold cathode in HVGD electrode systems that form electron beams with a linear focus.

GENERAL THEORETICAL APPROACHES AND THE BASIC EQUATIONS FOR CALCULATING THE TEMPERATURE DISTRIBUTION ON THE COLD CATHODE SURFACE OF HIGH-VOLTAGE GLOW DISCHARGE ELECTRON SOURCES

The main conclusion, which is a consequence of the general theory of HVGD, is that the accelerated electrons in HVGD do not significantly affect the temperature of the working gas [1]. Accordingly, limitations on the power of HVGD electron guns can only be associated with ensuring the dissipation of energy on the electrodes. In addition, the maximum power of HVGD electron guns is limited by the emissive properties of the cold cathode, as well as by contraction of the discharge and step ionization under conditions of high pressure [1]. The maximum value of the current density of the secondary ion-electron emission is $10^3\,A/m^2$. In any case, in the general theory of the HVGD, it is justified that, according to the relations for the current-voltage characteristic of the HVGD, the HVGD electron guns, within the physical conditions of the existence of the discharge under a defined range of the pressure and the accelerating voltage, are operated stably, without unwanted surges of current up to extremely high values [1].

The second conclusion of the general theory of HVGD is that to reduce the temperature of the electrodes and, accordingly, the effect of their heating on the discharge parameters, it is desirable to use light gases, for example, hydrogen or helium, in the powerful electron guns. In addition, it is known that when light gases are used, the sputtering coefficient of the cathode surface S decreases, and, accordingly, the operation time of the HVGD electron gun without replacing the cathode increases [1]. However, the choice of operation gas or gas mixture is always combined with the task of ensuring a high value of the coefficient of secondary ion-electron emission γ_g, which allows, under the condition of stable operation of the cathode, to increase the power of the electron beam that is formed [1–3]. Another way to reduce the operating temperature of the electrodes' surfaces is to increase the gas flow rate. However, the application of this method must be compatible with the gun current stabilization system, since the gun current depends on the pressure of the operation gas, and, according to the main equation of vacuum technology, the gas pressure in the HVGD gun directly depends on the gas flow rate [4]. Usually, in modern electron-beam technological equipment, the control of the current of the HVGD gun is carried out by changing the gas pressure by automatically adjusting the gas flow into the electron gun [4]. Therefore, this method of cooling is generally not used in industrial HVGD electron guns.

That is why ensuring the effectiveness of water cooling of the cold cathode due to the thermal power released on it as a result of bombardment with residual gas ions is the main technical factor that ensures the stable operation of HVGD electron guns [28].

Generally, the following four approaches are used to solve applied problems of thermodynamics [32–35].

1. A simplified approach based on the transition to a one-dimensional model without taking edge effects into account and solving the heat balance equation [32; 33]:

$$P_t + c_m(T)m_m \frac{dT_s}{dt} = P_b\,; \quad P_t = \int_0^{l_m} \frac{S_s(T_s - T_{cl})}{\lambda_m(T)} dl\,, \qquad (1)$$

where c_m is the specific heat capacity of the heated material; λ_m is the thermal conductivity of the heated material; S_s is the surface area irradiated by the flow of energetic particles; l_m is the thickness of the body being heated; T_s is the temperature on the surface of the substance, m_m is the mass of the heated material; T_{cl} is the temperature coolant; P_b is the power absorbed by the substance; and P_t is the lost power due to thermal conductivity.

Estimates of the surface temperature, which are based on relations (1), are most accurate for metals that have high thermal conductivity, and, due to this, the temperature of the surface of the metal, which is heated by a high-energy stream of charged particles, can be assumed to be the same with great accuracy [28]. Therefore, for the preliminary analysis of the temperature of the emission surface of the cathode of the HVGD electron guns, the ratio (1) is used. For electrode systems with direct cooling of the cathode by a coolant, the heat balance equation (1) is written as follows [28]:

$$T_c = \frac{W_c \dfrac{\gamma_g}{1+\gamma_g} \cdot \dfrac{R_c + l_c - \sqrt{R_c^2 - R^2}}{\lambda_c} + \dfrac{l_к}{\lambda_к}}{\alpha_c R_c^2 \left(\arcsin \dfrac{R}{2R_c} - \dfrac{R}{2R_c} \right)} + T_c\,, \quad \alpha_c = k_1 + k_2\sqrt{v_c}\,, \qquad (2)$$

where α_c is the heat transfer coefficient of the liquid through the base of the cathode; λ_c is the thermal conductivity of the cathode material; R_c — the radius of the cathode emission surface; R — the transversal size of the cathode; v_c is the rate of the cooling liquid, m^3/s, k_1 and k_2 are the empiric coefficients. For example, for water, at room temperature and atmospheric pressure, $k_1 \approx 350$ and $k_2 \approx 21000$ [34; 35].

In the case of a complex geometry of the cathode, a mathematical approach for describing the geometric form of complex three-dimensional objects, based on the application of arithmetic-logical relations [36] and Rvachov functions [37–39], or the locus, can be effectively used to find the temperature of its surface using relations (2). The appropriate software means can be effectively implemented using the programming tools of the MatLab system of scientific and technical calculations [40].

2. Analytical solution of the heat conduction equation [32; 33]:

$$\frac{\partial}{\partial t}(\rho c_v T) = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + F(x, y, z)\,, \qquad (3)$$

where x, y, and z are the space coordinates; T is the temperature of medium; λ is the thermal conductivity of the substance; ρ is its density by mass; $F(x, y, z)$ — the density of the thermal sources on the surface boundary.

Solving the generalized equation of thermal conductivity with partial derivatives (3) is carried out analytically by expanding its solution under given boundary conditions into a functional series. To carry out this operation, consider the kernel of equation (3), which, in its general form, is written as follows [28; 32; 33]:

$$\Phi(x,t) = \frac{1}{(2a_t\sqrt{\pi t})^n} \exp\left(-\frac{x^2}{4a_t^2 t}\right), \quad a_t^2 = \frac{\lambda}{\rho c_v}, \tag{4}$$

where x is the coordinate, that is under consideration and by which the equation (3) is solved; t is the time; a_t is the coefficient of thermal diffusion; c_v is the gas heat capacity by the volume, and n is the number of the basic function. In the theory of thermal conductivity, it has been proven that the series based on the use of functions (3) are orthogonal and coincide [41–44]. Generally, the coefficients of thermodynamic tasks in the functional row (4) must corresponded to partial differential equation (3), given above [28; 32; 33]. The general disadvantage of this approach is the difficulty of automating the formation of functional series using computer programs [32; 33]. That is, the application of such an approach requires a large amount of routine work from professional mathematicians and engineers. On the other hand, the obtained functional series can be analyzed, in particular, take the derivatives of analytical functions and search for their extrema [41; 42]. This sometimes, to some extent, simplifies the search for optimal engineering solutions regarding the geometry of the cathode assembly details [32; 33].

3. Numerical solution of the heat conduction equation (3). Usually, the right-hand difference method or the implicit Crank–Nicholson method is used to solve the complex non-stationary heat-conduction equation (3) [30; 31; 38]. However, if a stationary thermodynamic problem is considered, the hyperbolic heat conduction equation (3) is generally reduced to the elliptic Poisson equation [32; 33; 40; 43; 44]. The advantage of numerical methods for solving engineering problems in thermodynamics is that, if they are correctly set, it is possible to obtain high accuracy in modeling the temperature distribution, taking into account all edge effects. The general disadvantage of this approach is that, in order to obtain optimal designs of thermodynamic systems, it is necessary to analyze a large number of variants, which is usually associated with huge time costs. Today, even with the use of advanced computers and network technologies in cloud computing, solving one variant of an engineering task with the complex spatial geometry of the simulated object can take several hours [36; 39]. Another disadvantage of using this approach is that the research engineer has only the final results of the provided calculations, and after those, it is usually extremely difficult to find the optimal design from the point of view of the laws of thermodynamics. It is much easier to do this through the analysis of the simple analytical solution of a thermodynamic problem or the corresponding functional series.

4. Today, with the development of computer systems for engineering design and modeling, computer modeling methods using built-in computer calculation systems and engineering systems for automated design (CAD) are often used to estimate the temperature regimes of the HVGD cold cathode. Such methods of modeling thermodynamic systems are based on the numerical solution of the heat conduction equation (3) using the implicit Crank–Nicholson scheme, and calcula-

tions are performed using the finite element method [40; 43; 44]. When using this method, the accuracy of calculations for axially symmetric cathode cooling systems is proportional to the minimum dimensions of the calculation elements of the finite-difference cells and is estimated by the following ratio [43; 44]:

$$\varepsilon_2 = \sqrt{\left(\varepsilon_1 + \frac{\partial T(r,z)}{\partial r} h_r\right)^2 + \left(\varepsilon_1 + \frac{\partial T(r,z)}{\partial z} h_z\right)^2}\,, \tag{5}$$

where ε_1 is the temperature calculation error at nodal points; ε_2 is the error of approximation of the temperature dependence between nodes; h_r is the discretization step along the r coordinate, and h_z is the discretization step along the z coordinate.

It is clear from relation (5) that to increase the accuracy of simulation of HVGD cathode cooling systems, the density of the finite-difference grid should be increased in regions with a high temperature gradient. Usually, such areas are the boundaries between elements of the cooling system, which have different values of thermal conductivity.

The work [28] presented the results of modeling the cooling system of the cathode unit through the copper base in the case of considering a gap between the cathode and the base and without such a gap. The simulation was carried out in the **pdetool** program of the MatLab system for scientific and technical calculations [28; 40].

COMPUTER SIMULATION TOOLS OF THE SOLIDWORKS CAD SOFTWARE

The work [28] considered the means of modeling the cooling system of the cathode unit of the powerful HVGD electron gun, implemented in the modern **SolidWorks** software complex, in the **Flow Simulation** program [45; 46]. The advantage of using this software tool in engineering activities is that it is designed specifically for drawing and has high-quality graphic means for visualizing complex three-dimensional parts, assemblies and structures. In the **SolidWorks** software complex, drawings of individual parts of the cathode assembly are first created, and then, through the connection of these parts, an assembly drawing is performed with the possibility of three-dimensional visualization of the entire structure [45; 46]. After that, the final version of the drawing of the cathode assembly is uploaded to the **Flow Simulation** program, where the power of the heat flow that is applied to the surface of the cathode is set. Manual and automatic settings of the rate of the coolant are also possible. The **Flow Simulation** software has its own database on the necessary values of thermodynamic parameters of metals, ceramics, organic materials, as well as liquids and gases [45; 46], so it is enough to specify most of the material from which the corresponding part of the cathode assembly is made, the coolant and, if necessary, the type of operation gas and its pressure [45; 46]. Basic mechanical, thermodynamic, aerodynamic, and electrophysical properties of structural materials, given in reference literature [34, 35], already entered into the database of the **SolidWorks** CAD software [45; 46].

A generalized review of the possibilities of using all the approaches described above regarding the analysis and optimization of the temperature regime of the cathode cooling systems of HVGD electron guns was generally carried out in [28].

PRELIMINARY ESTIMATES OF THE TEMPERATURE OF THE COLD CATHODE SURFACE OF A HIGH-VOLTAGE GLOW DISCHARGE ELECTRON GUN, INTENDED FOR THE FORMATION OF A RIBBON ELECTRON BEAM, USING THE HEAT BALANCE EQUATION, ARITHMETIC-LOGICAL RELATIONS, AND RVACHOV FUNCTIONS

The structural diagram of the electrode system of the HVGD device, which forms a ribbon electron beam, is shown in Fig. 2. The device intended for the formation of a ribbon beam contains a cathode 1, which is fixed on a high-voltage insulator 4, and is located in a capsule 2. The cooling of the cathode surface with water is carried out directly, cold water enters through tubes that are passed through the insulator. The length of the rubber hoses used to supply water should be such that they provide reliable electrical insulation, taking into account the fact that a voltage of 15 kV is applied to the cathode.

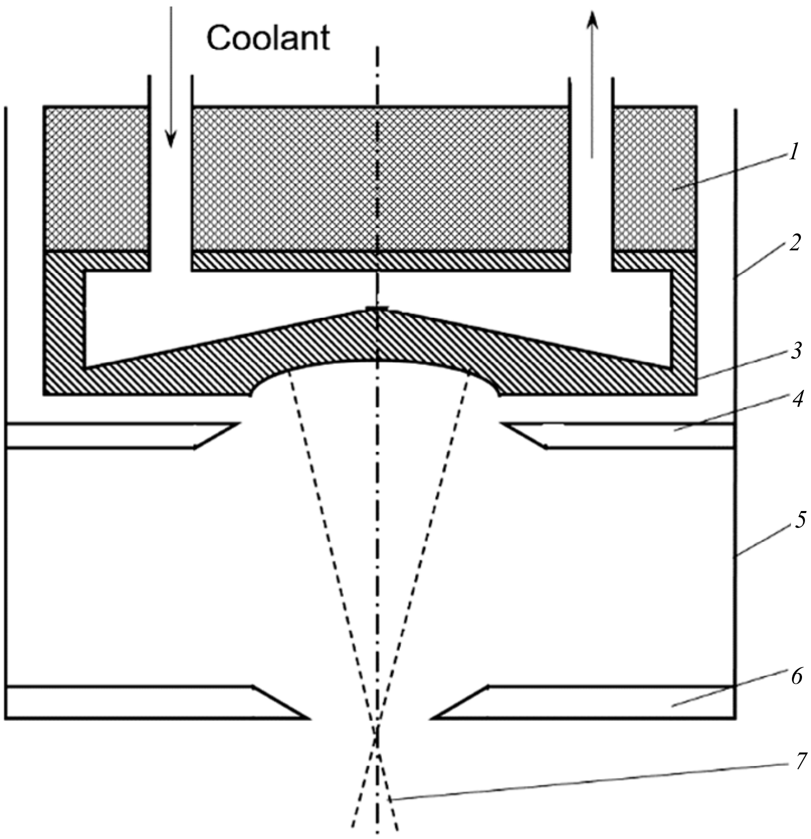


Fig. 2. Structural diagram of the HVGD electrode system designed to form a ribbon electron beam: *1* — insulator; *2* — capsule; *3* — cathode; *4* — near-cathode diaphragm; *5* — anode; *6* — base flange for mounting the gun on the technological chamber with a hole for the output of the electron beam; *7* — ribbon electron beam with a linear focus

The capsule of the device, taking into account the near-cathode diaphragm 4 and the base flange 6 with a hole for outputting the electron beam, forms a discharge chamber in which a high-voltage discharge burns [1–3]. Diaphragm 4, located near the cathode, ensures the distribution of the electric field necessary for the formation and focusing of the ribbon electron beam [2; 3].

The calculation of water cooling of the cathode surface for the HVGD electrode system, whose design scheme is shown in Fig. 2, was carried out taking into account the geometric features of the cathode assembly. Fig. 3 shows the construction of the cathode assembly used and the corresponding geometric parameters of the cathode. Therefore, the boundary conditions for solving thermodynamic task are presented in Fig. 4.

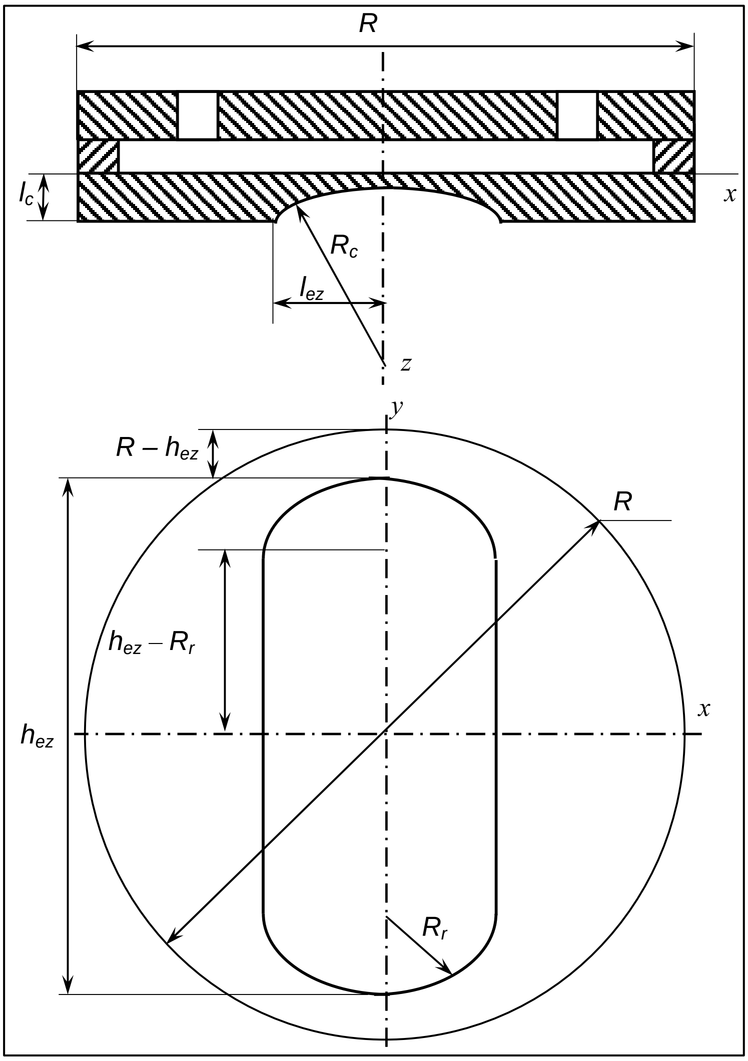


Fig. 3. Geometrical parameters of the cathode of the HVGD electrode system, the structural scheme of which is shown in *Fig. 2*: R_c is the radius of the cylindrical emission surface from which the flow of electrons is formed; R is the cathode radius as a structural element; l_c is the thickness of cathode; l_{ez} is the wideness of the cathode emission zone; h_{ez} is the longitude length of the cathode emission zone; and R_r is the radius of cathode rounding

Analytical relation (2) has been used to estimate the temperature of the surface of the HVGD cold cathode, and the geometry of the cathode assembly was described using arithmetic and logical functions [36]. Under such conditions, the arithmetic-logical relationship that was used to calculate the temperature of the cold cathode of the HVGD device, which forms a ribbon electron beam with a linear focus, has the following form:

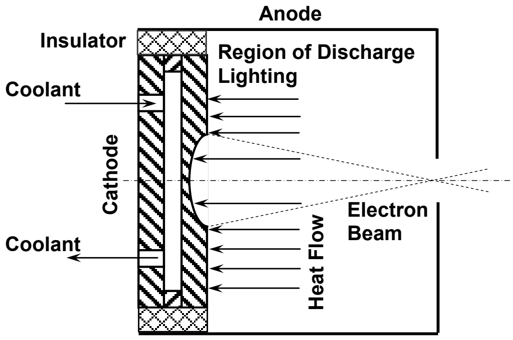


Fig. 4. The boundary conditions for calculation the heat regime of electrodes system of high voltage glow discharge electron gun

$$C_1 = ((|x| < l_{ez})\ \&\ (|y| < h_{ez})) \cdot \left(\frac{W_c \gamma_g \dfrac{R_c + 2l_c - \sqrt{R_c^2 - x^2}}{\lambda_c}}{\alpha_c R_c^2 (1+\gamma_g) \arcsin\left(\dfrac{l_{ez} - R}{2R_c}\right)} + T_{cl} \right),$$

$$C_2 = ((|x| \ge l_{ez})\ \&\ (|y| < h_{ez})\ \&\ (|x| \le R)) \left(\frac{W_c \gamma_g (R - l_{ez})}{\alpha_c R_c^2 \lambda_c (1+\gamma_g) \arcsin\left(\dfrac{R - R_r}{2R_c}\right)} + T_{cl} \right),$$

$$C_3 = \left(\left(|x| < \sqrt{R_r^2 - (|y| < h_{ez})^2} \right) \&\ (|y| \ge h_{ez})\ \&\ (|y| \le (h_{ez} + R)) \right) \times$$
$$\times \left(\frac{W_c \gamma_g \cdot \left(R_r + R_c - \sqrt{R_c^2 - x^2} \right)}{\alpha_c R_k^2 \lambda_k (1+\gamma_g) \arcsin\left(\dfrac{R - R_r}{2R_c}\right)} + T_{cl} \right), \qquad (6)$$

$$C_4 = \left(\left(|x| \ge \sqrt{R_r^2 - (|y| < h_{ez})^2} \right) \&\ (|y| \ge h_{ez})\ \&\ (|y| \le (h_{ez} + R)) \right) \times$$
$$\times \left(\frac{W_c \gamma_g l_c}{\alpha_c \lambda_c (1+\gamma_g) \left(R - \sqrt{R_r^2 - (|y| - h_{ez})^2} \right)^2 \arcsin\left(\dfrac{R - R_r}{2R_c}\right)} + T_{cl} \right),$$

$$C_5 = (|y| > h_{ez}) \left(\frac{W_c \gamma_g l_c}{\alpha_c R_c^2 (1+\gamma_g)} + T_{cl} \right), \quad T_c(x,y) = C_1 + C_2 + C_3 + C_4 + C_5,$$

where $T_c(x,y)$ is temperature distribution function on the cathode surface by x and y coordinates; α_c is the heat transfer coefficient of the coolant liquid through the base of the cathode according to the second ratio of equations set (2).

Calculations using relations (6) were carried out using logical and matrix programming tools of the MatLab -system of scientific and technical calculations for the following parameters of the cathode assembly: $T_{cl} = 10\,^{\circ}$C, $W_c - 1 - 5$ kW, $\gamma_g = 3$, $R_c = 0.05$ m, $R = 0.03$ m, $R_r = 0.012$ m, $l_c = 0.005$ m, $l_{ez} = 0.012$ m, $h_{ez} = 0.026$ m, $v_c = 0.03\,\text{m}^3/\text{s}$, $k_1 = 350\,k$ and $k_2 = 21000$.

The simulation results obtained using arithmeticlogical relations (6) are shown in Fig. 5.

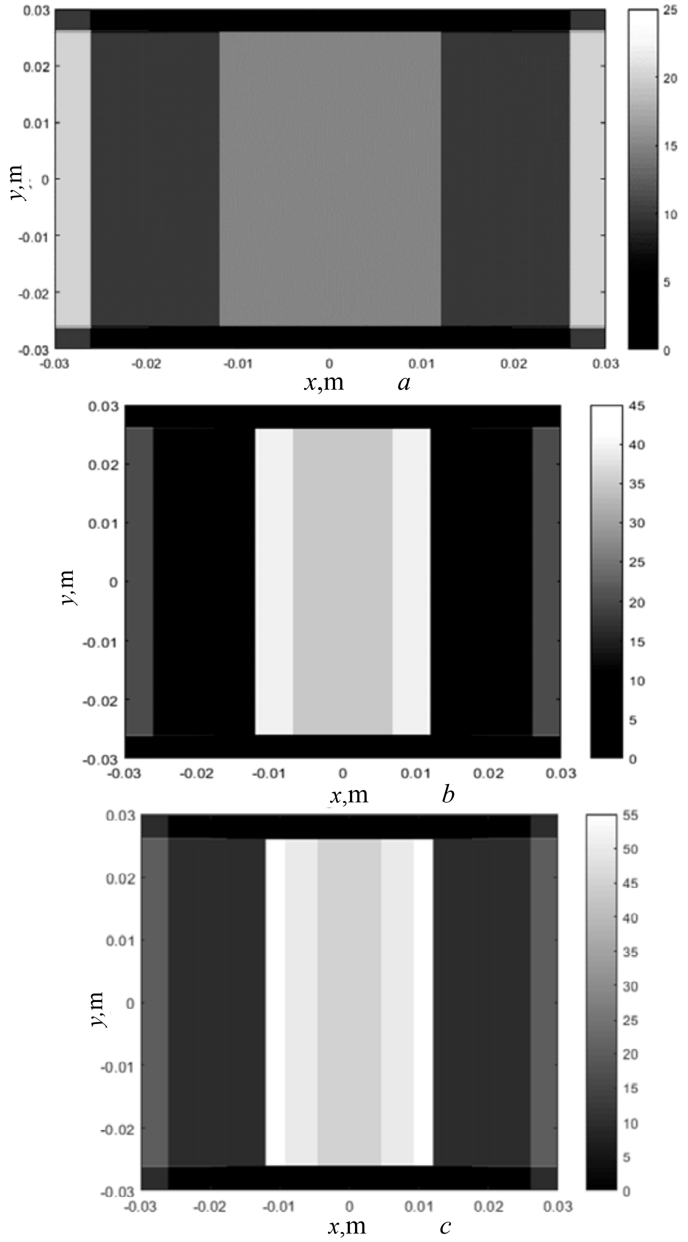


Fig. 5. Contour graphs of the temperature distribution on the cold cathode surface $T_c(x, y)$, obtained using arithmetic-logic relation (6): *a* — $W_c = 1$ kW; *b* — $W_c = 5$ kW; *c* — $W_c = 7$ kW

From the graphic dependences obtained using arithmetic-logic relations (6) and shown in Fig. 5, it can be seen that the preliminary, generalized estimates based on the use of the heat balance equation indicate that in the range of power released at the cathode, within the range of $W_c = 1 - 7$ kW, the surface temperature of the water-cooled aluminum cathode does not exceed 60°C. Such a temperature mode of operation is normal for the cold cathode of technological electron sources, based on HVGD [1–3].

Another, more accurate approach to describing the geometry of complex three-dimensional objects is the use of Rvachev functions, or locus [37–39]. The essence of this approach is that instead of the logical ratios used in the analytical expression (6), atomic functions or locus are used. Locus is smooth functions with a high value of the derivative. Therefore, with their help, a jump-like coordinate difference is approximated for the surface being modulated. Locus functions are formed on the basis of arithmetic-logical relations. This approach makes it possible to effectively use locus for solving problems of electrophysics and thermodynamics in real devices with complex electrode geometry [37–39].

Analytical expressions for locus functions are given in Table 1 [35–37].

Table 1. Rvachov R-functions R_α, or locus

The accompanying logical function of the Boolean algebra	**Set of functions** R_α
$F_1(x_1, x_2) = x_1 \wedge x_2$	$y_1(x_1, x_2) = x_1 \wedge_\alpha x_2 = \frac{1}{1+\alpha} \times \left(x_1 + x_2 - \sqrt{x_1^2 + x_2^2 - 2\alpha x_1 x_2} \right)$
$F_2(x_1, x_2) = x_1 \vee x_2$	$y_2(x_1, x_2) = x_1 \vee_\alpha x_2 = \frac{1}{1+\alpha} \times \left(x_1 + x_2 + \sqrt{x_1^2 + x_2^2 - 2\alpha x_1 x_2} \right)$
$F_3(x_1) = \bar{x}_1$	$y_3(x_1) = \bar{x}_1 = -x_1$

The coefficient α in the ratios given in Table 1 is selected in the range [0; 1], depending on the formulation of the modeling task.

Let's rewrite the logical expressions of the arithmetic-logical functions (6) in terms of the Rvachev R_α functions defined in Table 1.

$$L_{11} = (l_{ez} - |x|); \quad L_{12} = (h_{ez} - |y|);$$

$$R_1(L_{11}, L_{12}) = L_{11} \wedge_\alpha L_{12} = \frac{1}{1+\alpha} \times \Big((l_{ez} - |x|) + (h_{ez} - |y|) -$$

$$- \sqrt{(l_{ez} - |x|)^2 + (h_{ez} - |y|)^2 - 2\alpha (l_{ez} - |x|)(h_{ez} - |y|)} \Big);$$

$$L_{21} = (|x| - l_{ez}), \quad L_{22} = (h_{ez} - |y|), \quad L_{23} = (R - |x|);$$

$$R_{21}(L_{21}, L_{22}) = L_{21} \wedge_\alpha L_{22} = \frac{1}{1+\alpha} \times \Big((|x| - l_{e3}) + (h_{e3} - |y|) -$$

$$- \sqrt{(|x| - l_{ez})^2 + (h_{ez} - |y|)^2 - 2\alpha (|x| - l_{ez})(h_{ez} - |y|)} \Big);$$

$$R_2(R_{21}, L_{23}) = R_{21} \wedge_\alpha L_{23} = \frac{1}{1+\alpha} \times \Big(R_{21} + (R - |x|) - \qquad (7)$$

$$- \sqrt{R_{21}^2 + (R - |x|)^2 - 2\alpha R_{21} (R - |x|)} \Big);$$

$$L_{31} = |x| - \sqrt{R_r^2 - (|y| < h_{ез})^2}, L_{32} = |y| - h_{ez}, L_{33} = (h_{ez} + R) - |y|;$$

$$R_{31}(L_{31}, L_{32}) = L_{31} \wedge_\alpha L_{32} = \frac{1}{1+\alpha} \times \left(\left(|x| - \sqrt{R_r^2 - (|y| - h_{ez})^2} \right) + (|y| - h_{ez}) - \right.$$

$$\left. - \sqrt{\left(|x| - \sqrt{R_r^2 - (|y| - h_{ez})^2} \right)^2 + (|y| - h_{ez})^2 - 2\alpha \left(|x| - \sqrt{R_r^2 - (|y| < h_{ez})^2} \right)(|y| - h_{ez})} \right);$$

$$R_3(R_{31}, L_{33}) = R_{31} \wedge_\alpha L_{33} = \frac{1}{1+\alpha} \times \left(R_{31} + ((h_{ez} + R) - |y|) \right. -$$

$$\left. - \sqrt{R_{31}^2 + ((h_{ez} + R) - |y|)^2 - 2\alpha R_{31}((h_{ez} + R) - |y|)} \right);$$

$$L_{41} = \sqrt{R_r^2 - (|y| < h_{ez})^2} - |x|, L_{42} = |y| - h_{ez}, L_{43} = (h_{ez} + R) - |y|;$$

$$R_{41}(L_{41}, L_{42}) = L_{41} \wedge_\alpha L_{42} = \frac{1}{1+\alpha} \times \left(\left(\sqrt{R_r^2 - (|y| - h_{ez})^2} - |x| \right) + (|y| - h_{ez}) - \right.$$

$$\left. - \sqrt{\left(\sqrt{R_r^2 - (|y| - h_{ez})^2} - |x| \right)^2 + (|y| - h_{ez})^2 - 2\alpha \left(\sqrt{R_r^2 - (|y| < h_{ez})^2} - |x| \right)(|y| - h_{ez})} \right);$$

$$R_4(R_{41}, L_{43}) = R_{41} \wedge_\alpha L_{43} = \frac{1}{1+\alpha} \times \left(R_{41} + ((h_{ez} + R) - |y|) \right. -$$

$$\left. - \sqrt{R_{41}^2 + ((h_{ez} + R) - |y|)^2 - 2\alpha R_{41}((h_{ez} + R) - |y|)} \right);$$

$$L_5 = |y| - h_{ez};$$

$$R_5(L_5, 1) = L_5 \wedge_\alpha 1 = \frac{1}{1+\alpha} \times \left((|y| - h_{ez}) + 1 - \sqrt{((|y| - h_{ez}))^2 - 2\alpha(|y| - h_{ez}) + 1} \right).$$

Then the sophisticated arithmetic-logical relation (6), taking into account (7), will be rewritten as follows:

$$T_c(x, y) = R_1 \left(\frac{W_c \gamma_g \dfrac{R_c + 2l_c - \sqrt{R_c^2 - x^2}}{\lambda_c}}{\alpha_c R_c^2 (1 + \gamma_g) \arcsin\left(\dfrac{l_{ez} - R}{2R_c} \right)} + T_{cl} \right) +$$

$$+ R_2 \left(\frac{W_c \gamma_g (R - l_{ez})}{\alpha_c R_c^2 \lambda_c (1 + \gamma_g) \arcsin\left(\dfrac{R - R_r}{2R_c} \right)} + T_{cl} \right) +$$

$$+R_3\left(\frac{W_c\gamma_g\left(R_r+R_c-\sqrt{R_c^2-x^2}\right)}{\alpha_c R_c^2\lambda_c(1+\gamma_g)\arcsin\left(\dfrac{R-R_r}{2R_c}\right)}+T_{cl}\right)+ \qquad (8)$$

$$+R_4\cdot\left(\frac{W_c\gamma_g l_c}{\alpha_c\lambda_c(1+\gamma_g)\left(R-\sqrt{R_r^2-(|y|-h_{ez})^2}\right)^2\arcsin\left(\dfrac{R-R_r}{2R_c}\right)}+T_{cl}\right)+$$

$$+R_5\left(\frac{W_c\gamma_g l_c}{\alpha_c R_c^2(1+\gamma_g)}+T_{cl}\right).$$

The results of calculating the temperature distribution on the surface of the cathode using content (8), which have been obtained under the condition α = 0.95, are shown in Fig. 6.

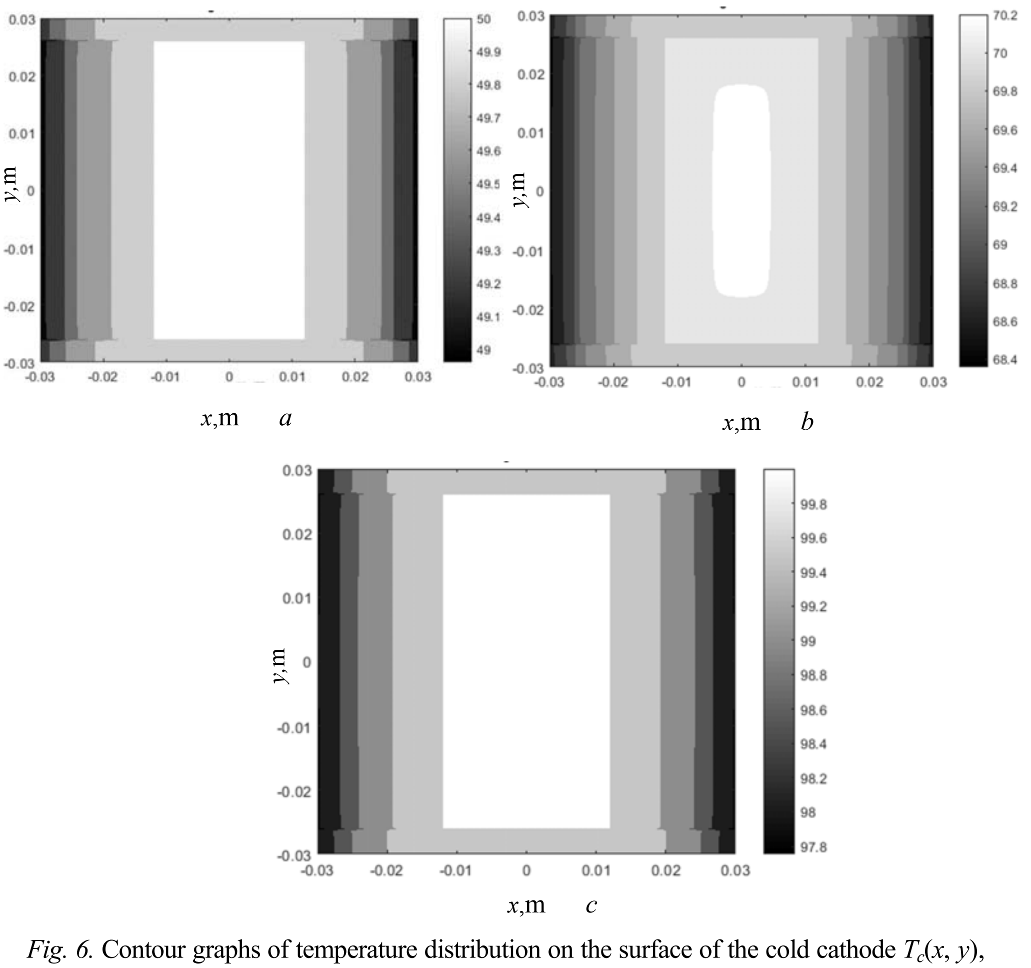


Fig. 6. Contour graphs of temperature distribution on the surface of the cold cathode $T_c(x, y)$, obtained using relation (8): *a* — $W_c = 1\,\text{kW}$; *b* — $W_c = 3\,\text{kW}$; *c* — $W_c = 5\,\text{kW}$

ESTIMATION OF THE SURFACE TEMPERATURE OF THE COLD CATHODE USING MODELING TOOLS OF THE SOLIDWORKS CAD SOFTWARE

The CAD software system **SolidWorks** is a well-known and widely used package that allows one to create 3D models of parts based on drawings or sketches. That is why this engineering CAD is often used by designers and industrialists. The system also has the powerful algorithms for calculating loads of various types. The calculations are based on the physical parameters of materials implemented in the program, which include almost all widely used metals, alloys, nonmetals, and liquids. Mechanical loads and deformations, as well as thermal loads can be simulated. It is also possible in this CAD system to study the aerodynamics or hydrodynamics of a simulated object in a liquid or gas flow [45; 46].

Today, the creation of an engineering design of any device cannot be done without the prior use of its simulation tools. High-voltage devices, in case of failure during testing, pose a significant danger, therefore, it is much more efficient and safer to make their preliminary modeling and corresponding simple calculations. Modern systems of automatic design and their corresponding tools allow, with sufficient accuracy, to simulate the conditions and loads to which a real model of the device will be subjected. The **SolidWorks** CAD system has several internal applications for modeling loads of various types [45; 46].

In the course of the provided engineering researches described in this section of paper, the application **Flow Simulation** has been used [45; 46]. This program allows you to simulate flows of liquids or gases within certain geometric limits, taking into account the heat exchange between interacting solid-states materials, liquids, and gases. Since this software is primarily focused on the development of three-dimensional models, it calculates the physical parameters of materials with a certain value of error, which does not allow obtaining an absolutely accurate result. However, usually this accuracy of calculations is sufficient to draw general conclusions regarding the correctness of testing and applying the system being researched and designed [45; 46].

To simulate the design of the device in the **SolidWorks** CAD system, one need to make an assembly drawing or a necessary detail in the form of a three-dimensional model. In the provided and described engineering research, an assembly drawing of an electronic device intended for the formation of an electron beam with a ribbon focus has been made. First of all, one needs to open the assembly drawing file and click on the option **Flow Simulation**.

In the next step, one needs to create a new project with specification of physical quantities, materials, and initial conditions for modeling.

Then, by selecting the **Calculation Area** option, one can select the space where the object of research is located. Before this, it is necessary to make an axisymmetric section of the assembled drawing for better visualization [28; 45; 46].

As noted in Section 4 of the paper, the **SolidWorks** CAD system has its own powerful database of mechanical, electrical, and electrophysical properties of various structural materials. Therefore, the next step in simulation is the selection of materials from which separate parts of the structure are made. If the necessary material is not available, it is possible to create a new record in the database and enter the necessary parameters of the material there [45; 46].

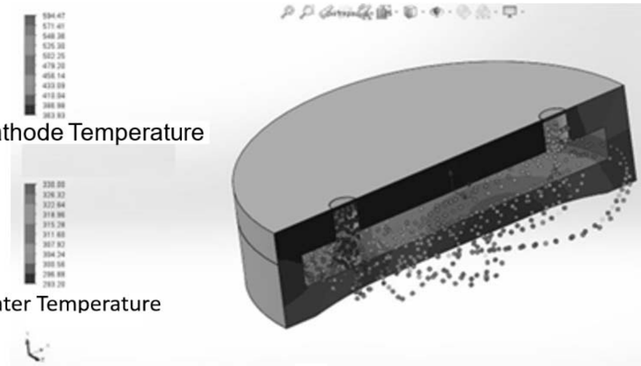
Having chosen the materials for the parts and assemblies of the device, one can move on to defining the boundary conditions for the operation of the device being modeled [45; 46]. The parameters of the model for studying the temperature mode of operation of the cathode unit of the HVGD electron gun, which forms a ribbon beam with a linear focus, are given in Table 2.

Table 2. The parameters of the cathode assembly model of the HVGD electron gun, which forms an electron beam with a linear focus, created in the **SolidWorks** CAD system

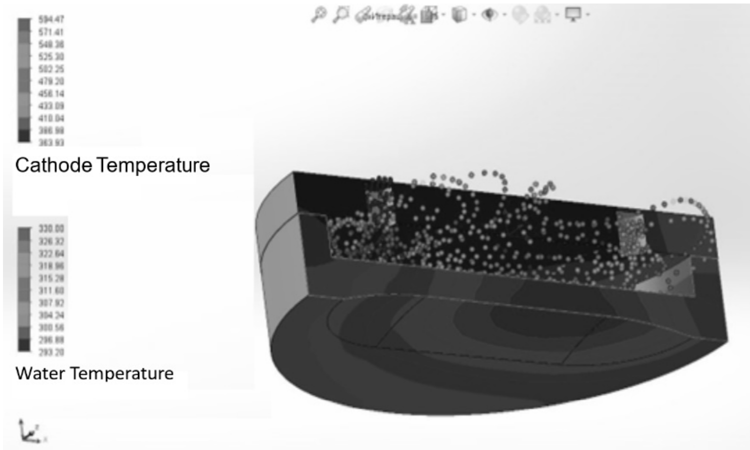
Model parameter	**Value**	
A model of the heat conduction in a solid body	Enabled	
Only heat conduction in a solid	Disabled	
Radiation heat exchange	Disabled	
Heat exchange in gas by radiation	Disabled	
Non-stationarity	Disabled	
Gravitational effects	Disabled	
Rotation	Local Area (Averaging)	
The power released at the cathode	2 kW	
Type of liquid flow	Laminar and turbulent	
High-value Mach number flow model	Disabled	
Cavitation	Enabled	
Concentration of dissolved gas by mass, kg/m^3	10^{-4}	
Free surface	Disabled	
Surface roughness, μm	0.1	
Water flow rate in the normal direction to the cathode surface, m/s	10	
Water consumption, m^3/s	10^{-5}	
Thermal conditions on the outer walls	Adiabatic wall	
Number of nodes in the finite-elements mesh	$5 \cdot 10^3$	
Thermodynamic parameters	Static pressure, Pa	Temperature, °K
	101325	293.2
Intensity and scale of turbulence	Intensity, %	Scale (length, m)
	2	$1.5 \cdot 10^{-4}$

ANALYSIS OF OBTAINED SIMULATION RESULTS AND PRACTICAL RECOMMENDATIONS

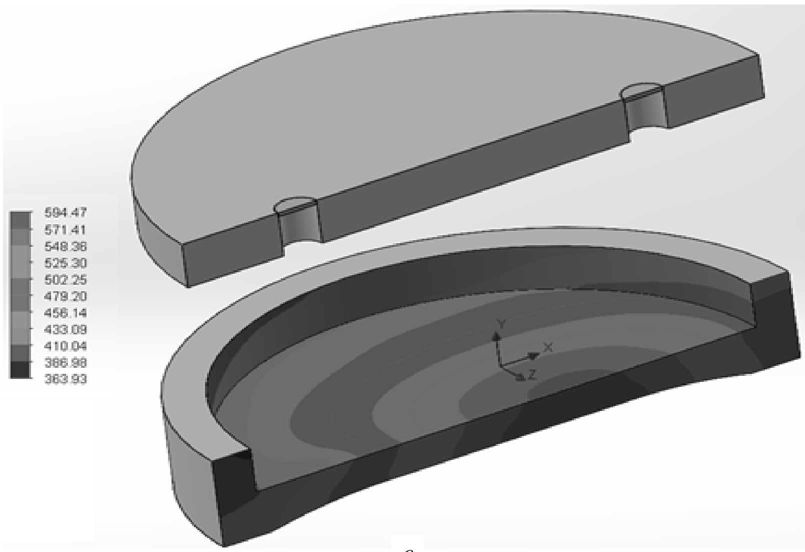
Fig. 7 shows the results of modeling the thermal modes of operation of the cathode node of an electronic device that forms a ribbon beam with a linear focus, obtained using the **Flow Simulation** program in the **SolidWorks** engineering computer CAD system. The obtained results largely coincide with the results obtained by numerically solving the heat balance equation and modeling the geometry of the cathode node by arithmetic-logical relations or locus functions, which are shown in Fig. 6.



a



b



c

Fig. 7. The temperature distribution of the cathode assembly T_c (*x*, *y*, *z*), obtained using modeling tools and the design toolkit of the SolidWorks CAD software

The results of modeling the temperature regime of the cathode assembly obtained in the provided research generally indicate that a simplified approach to solving the heat conduction equation (3), connected with the transition to the analytical solution of the heat balance equation (2), taking into account the real geometry of the cooling constructive elements of the electronic gun through the use of arithmetic-logical relations, is quite effective, and the accuracy obtained from modeling is usually sufficient for preliminary generalized estimates of the thermal mode of operation of structural units at the initial stage of gun design. The method of describing the complex geometry of construction details by locus or Rvachev functions [28; 37–39] is also effective. To calculate the thermal regime of the cathode assembly, we used relation (2), which is quite universal and was used in work [28] to calculate the surface temperature of the cathode with direct cooling in electron guns that form beams with a point focus. The difference of the proposed model lies in the fact that the real geometry of the cathode assembly for the HVGD electron guns, which forms a ribbon electron beam, was described using the appropriate arithmetic-logical ratios. It should also be noted that the accuracy of thermal calculations in the SolidWorks software complex is also low, about 20%. However, an important advantage of this system, from a practical point of view, is the possibility of numerical calculations for real structures. In this regard, if the appropriate mathematical apparatus is available, the proposed model of the cathode node, based on the use of locus, or Rvachev functions [28; 37–39], can be recommended to designers of electron beam technological equipment for further practical use. To carry out more accurate estimates of the temperature of the surface of the cathode, taking into account the boundary effects, in work [28] it was recommended to use the **pdetool** toolkit of the MatLab system of scientific and technical calculations, however, working with this program requires certain qualifications and knowledge of the appropriate mathematical apparatus from the designers.

The testing experiments in SolidWorks software were realized in the such range of geometry parameters of cathode item: $R_c = 0.05 \pm 0.01$ m, $R = 0.03 \pm \pm 0.01$ m, $R_r = 0.012 \pm 0.01$ m, $l_c = 0.005 \pm 0.001$ m, $l_{ez} = 0.012 \pm 0.001$ m. By the power of electron gun regimes, range of 1–150 kW are considered. Pointed out above error of simulation, corresponding to the obtained experimental results, have been in the same range. The dependences of focal beam parameters on geometry of electrodes' system and technological tolerances have been analyzed in the papers [22–24].

The scientific results, given in this article, have been obtained in the Scientific Laboratory of Electron Beam Technological Devices of National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnical Institute" customed by "Chervona Khvyla" Open Joint Stock Company.

These results are of interest to a wide range of specialists who are engaged in the development and introduction into production of modern electron-beam technological equipment.

CONCLUSION

The paper considers various theoretical approaches to estimating the operating temperature of the surface of the cold cathode of the HVGD electron gun, which forms a ribbon-like converging electron beam with a linear focus. Based on the test calculations that have been performed, it is shown that the accuracy of estimates using ratio (2), obtained as a solution of the system of heat balance equations (1), is quite high. For the considered models of HVGD electron guns, the calculated surface temperature of the cathode, in the case of using Rvachev arithmetic-logical relations and functions (8) to describe the geometry of the cathode assembly, is about 5–10% and is close to the estimated results obtained using the **SolidWorks** software complex. To carry out more accurate estimates, taking into account edge effects and the influence of the temperature of the peripheral region of the cathode on the emission of electrons from its surface, you can use either estimates through functional series using relation (4) or the **pdetool** toolkit of the MatLab scientific and technical calculations system. The method of using ratio (4) to estimate the surface temperature of the cathode of the HVGD electron gun, which forms a beam with a point focus, as well as the corresponding mathematical approaches for the use of special functions, were considered and analyzed in work [28]. Such evaluations can be interesting and useful for developers of new types of HVGD electron guns with improved emission characteristics. To carry out such calculations, a sufficiently high qualification of development engineers with appropriate knowledge of mathematical functions and corresponded software is required. In the case of preliminary evaluations, without taking into account the influence of the temperature of the peripheral region of the cathode surface on its emission characteristics, calculations using arithmetic-logical relations and Rvachev functions similar to relations (8) are sufficient. To carry out such assessments, it is also necessary to develop suitable mathematical approaches and appropriate modifications of the software, since each design of the HVGD electron guns for technological purposes has its own specific features [2; 3].

Main recommendations to engineers, who designed HVGD electron guns, have been obtained as a results of scientific research, are as follows.

1. For electron guns with the power range of 1–5 kW using of cathode item without cooling for simplifying the gun construction is possible.

2. For electron guns with the power range of 5–30 kW using of cooling cathode through cooper base for simplifying the gun construction is possible.

3. For electron guns with the power, grater, then 30 kW, the direct cooling of the cathode surface with coolant is necessary. The scheme of corresponded gun construction is given in Fig. 2, and the geometrical parameters are noted at Fig. 3. The temperature of cathode emission surface for the cathode from aluminum has to be in range 150–200 $^{\circ}$C [2; 28].

The theoretical assumptions presented in the article are of great practical importance regarding the creation of new types of structures for HVGD electron guns and their industrial application. The results presented in the article may be interesting and useful for a wide range of specialists who are engaged in the development of modern electron-beam equipment and its application in industry.

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ОЦІНЮВАННЯ ТЕПЛОВОГО РЕЖИМУ РОБОТИ КАТОДА ЕЛЕКТРОННИХ ГАРМАТ ВИСОКОВОЛЬТНОГО ТЛІЮЧОГО РОЗРЯДУ, ЯКІ ФОРМУЮТЬ СТРІЧКОВИЙ ЕЛЕКТРОННИЙ ПУЧОК / І.В. Мельник, С.Б. Тугай, Д.В. Ковальчук, М.С. Суржиков, І.С. Швед, М.Ю. Скрипка, О.М. Коваленко

Анотація. Розглянуто різні способи оцінювання температури поверхні катода електронної гармати високовольтного тліючого розряду (ВТР), яка формує стрічковий електронний пучок з лінійним фокусом. Оцінювання виконано для конструкції катодного вузла гармати промислового призначення. Показано, що найбільш ефективним для проведення наближених оцінок температури поверхні катода в гарматах ВТР різного технологічного призначення є використання арифметико-логічних співвідношень для моделювання геометрії катодного вузла та локусів для оцінювання розподілу температури. Точність оцінювання, проведеного з використанням рівняння теплового балансу, складала 5–10%, що є достатнім на початковому етапі проектування електронної гармати. Показано, що використання для проектування електронних гармат ВТР програмного комплексу CAD SolidWorks є ефективним лише для вирішення завдань комплексного інженерного проектування гармат ВТР та оформлення відповідної технічної документації. Результати теоретичних досліджень є цікавими для широкого кола фахівців, які займаються розробленням електронно-променевого обладнання та його впровадженням у промислове виробництво.

Ключові слова: електронна гармата, високовольтний тліючий розряд, автоматизоване проектування, рівняння теплопровідності, рівняння теплового балансу, арифметико-логічне співвідношення, функції Рвачова.