Investigation of the thermal state of the elements of a technological electron beam gun under long-term operating conditions

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Abstract. The paper presents the results of a study of the thermal state of the elements of the cathode assembly of the ELA‒15 welding electron gun. It was revealed that in short‒term operating modes of the gun (up to 60 minutes) at any energy parameters of heating the hexaboride cathode, it is possible not to use forced cooling of the cathode assembly. The case temperature in such modes did not exceed 30˚С. The increase in the temperature of the gun body occurred 15 minutes after the start of heating the cathode. In long‒term operating modes with forced cooling of the gun, the temperature of the gun body increased by 2 ‒ 3°C and remained stable throughout the operation. When the cooling was turned off, the temperature of the gun body reached a critical value in 60 minutes. The section of natural cooling of the cathode obtained in the work, which appears when the heating of the cathode is stopped, is well approximated by a power function. It is convenient to use this dependence to verify the mathematical model of the thermal state of the electron gun.

1. Introduction

Technological welding electron gun is a complex high‒voltage electric vacuum device. In the electron gun, a powerful axially symmetric focused electron beam is formed, which is used to obtain a welded joint. The stability of the energy and spatial parameters of the electron beam has a great influence on the quality of the weld [1]. Electron guns with thermionic cathodes are widely used in welding production [2, 3]. In turn, such guns have two main designs: a gun with a directly heated cathode [4, 5] and a gun with an indirectly heated cathode [6, 7]. Direct‒heated cathodes are more expedient to use at low current densities or short operating cycles [8]. The heating of the cathode in the direct‒heated circuit to the required temperature is carried out due to the direct flow of current through the cathode. The main problem with such a scheme is the low power of the resulting beam (up to 45 kW). To obtain a high‒power beam in a directly heated system, it is necessary to increase the area of the working surface of the cathode. An increase in the surface will lead to an increase in the filament current, which will cause an increase in the magnetic field in the cathode area, which will affect the geometry of the resulting beam [9]. In addition, heat removal from the cathode area will become much more difficult, and there will be a need to increase the cross‒section of the high‒voltage cable, which will make the design more complex and expensive [10].

To obtain a high‒power beam, an indirect cathode heating system is used. The main cathode is most often made of lanthanum hexaboride (LaB6) [10]. Such a cathode is distinguished by insignificant power
consumption for heating, which contributes to lower temperature deformations of the cathode assembly [1]. The use of such a heating scheme makes it possible to avoid the transmission of high heating currents through the high-voltage cable, thereby increasing the reliability of the gun. The main cathode is heated by electron bombardment from the auxiliary cathode. The main disadvantage of this scheme is the need to stabilize the temperature of the main cathode. The main reason for the temperature instability of the main cathode is additional heating of the auxiliary cathode due to radiation from the main cathode. Also, there is a change in the emission characteristics of both cathodes due to thermochemical destruction [11].

A completely new solution in the indirect heating system is the use of a main metal cathode instead of a lanthanum hexaboride cathode. The metal cathode is more resistant to poisoning by the products of chemical reactions and the effects of ion bombardment. As a result, the service life of such a cathode is longer than that of a hexaboride one. To ensure the required emission from the metal cathode, it is necessary to increase the heating power of the cathode, which in turn will lead to an increase in the heat load on the elements of the cathode assembly.

The cathode heated to high temperatures is the main source of heat in the electron gun. Under the influence of thermal conductivity and radiation, heat spreads through the elements of the cathode assembly and the insulator, thereby increasing their temperature. The soldering points of the high-voltage insulator are subject to overheating, which can lead to a leakage of the accelerating gap and the high-voltage bushing chamber. Most guns have a liquid cooling system to remove heat. But due to the high electric voltages on the elements of the cathode assembly, the heat removal area is located on the gun body and is located at a sufficiently large distance from the heat source. For more intense heat removal, insulating liquids such as transformer oil or organosilicon are used [12].

The main problem in assessing the thermal state of the gun during operation is the inability to control the temperature of its working elements. It is almost impossible to install measuring instruments such as a pyrometer or thermocouple in the area of the cathode assembly due to limited access and high electrical voltages. To monitor the temperature state, manufacturers of electron guns use temperature sensors, which are most often located on the body of the gun. This solution allows you to indirectly assess the state of the elements of the cathode assembly. However, the time interval that allows registering the change in the temperatures of the elements of the cathode assembly according to the temperature of the body is rather long. Overheating of the main and auxiliary cathodes leads to a decrease in their resource, as well as to a change in the geometry of the accelerating gap due to thermal expansion. A high probability of overheating arises when, during the operation of the gun, the cathode is in a heated state for a long time.

The geometry of the accelerating gap strongly affects the characteristics of the generated beam and, as a consequence, the quality of the resulting weld. It is known that a change in the cathode–anode interelectrode distance affects the shape of the penetration channel with a slight change in its depth [14], and when the position of the control electrode relative to the cathode changes, the condition for blocking and focusing of the accelerating gap changes [9, 15]. There are many reasons for changing the geometry of the accelerating gap. One of the reasons, as already mentioned, is the thermal expansion of the elements of the cathode assembly. Thermal expansion most of all affects the relative position of the cathode and gate. When heated, the cathode will move out relative to the control electrode. The problem in this case is the complexity of real assessment of the mutual change of electrodes. Due to limited access during the operation of the electron gun, it is impossible to visually assess the geometry change. The only possible way is mathematical modeling of thermal processes. However, when choosing this approach, another problem arises – the reliability of the obtained simulation results. Validity problems can be solved by verifying the model.

The purpose of the work is to study the effect of various parameters of heating the cathode on the thermal state of the elements of the cathode assembly.
2. Research methodology

The object of investigation in this work was an ELA–15 electron gun with an accelerating voltage of 60 kV and a beam power of up to 15 kW, developed by the E.O. Paton Electric Welding Institute (Figure 1). The gun has a classic three–electrode accelerating gap: cathode, control electrode, and anode. The cathode has an indirect heating system. The main cathode is made of lanthanum hexaboride (LaB6) and is in the form of a tablet. The auxiliary cathode is a spiral. The heating of the cathode by electron bombardment is carried out using a system similar to a vacuum diode. The auxiliary cathode is heated by direct current flow through its spiral. A potential difference is applied between the auxiliary spiral cathode and the main cathode, accelerating the emitted electrons towards the main cathode. As a result, electrons bombard the main cathode, heating it to operating temperature. The maximum power delivered by the bombardment and incandescence source is 50 watts. The working temperature of the lanthanum hexaboride cathode is 1500 – 2000 K, the coil heats up to 2700 K.

![Figure 1](image_url)

Figure 1 – three–dimensional model of the cathode unit of the ELA–15 welding gun: (a) general view; (b) area of beam generation; 1 – main cathode; 2 – cathode holder; 3 – cathode sleeve; 4 – heater thread; 5 – heater; 6 – high–voltage insulator; 7 – high–voltage connector; 8 – gun body; 9 – high–voltage input chamber; 10 – tubular refrigerator.

Most of the heat is released at the main cathode. The cathode is fixed in a special holder in the shape of a plate. Holder material – molybdenum [12]. The main reason for using molybdenum is its high melting point. The holder is attached to the high–voltage insulator using a special cathode sleeve. Most often, the sleeve is made from austenitic grade stainless steel. The heat at the cathode, obtained as a result of electron bombardment, begins to be removed from it to the high–voltage insulator due to thermal conductivity. Another source of heat in the cathode assembly is the heated tungsten filament of the auxiliary cathode. The heater assembly is also mounted on the insulator. The heater begins to transfer heat from the filament to the high–voltage insulator. In addition to all this, the elements of the cathode assembly are heated by radiation. This primarily concerns the control electrode, which heats up as a result of radiation from the main cathode and its holder.
To remove heat from the high-voltage insulator, an insulating liquid is poured into the high-voltage bushing chamber, which also provides the electrical strength of the bushing [12]. The liquid is cooled by a liquid tubular cooler in the form of a coil immersed in an insulating liquid.

In the ELA gun, to assess the thermal state, the manufacturer provides a resistance thermal conversion sensor. According to the manufacturer, its readings allow us to estimate the temperature of the insulating liquid. The sensor is mounted on the outside of the cathode assembly housing. The sensor body is made of brass in the form of a bar with dimensions 6x6x43. This allows you to simply attach it to the body of the gun using a conventional clamp. The critical temperature at which the unit is shut down is 30 °C. The criteria for choosing this particular temperature are unknown. The main disadvantage of such a sensor is its size. The area of its contact with the body of the gun is quite large. As a result, the measured temperature has an average value over the area of contact with the housing. There is usually a temperature gradient across the gun body. The top of the gun is hotter than the bottom. This feature is due to the convection of the insulating liquid.

To assess the thermal state of the elements of the cathode assembly of the welding electron gun, an experimental stand was developed (Figure 2). The stand allows evaluating and recording the cathode heating temperature and the gun body temperature, as well as synchronously recording the parameters of the cathode bombardment.

A chromel–alumel thermocouple was used as a temperature sensor for the gun body. The sensor was installed on the outer wall of the gun body. Its location is shown in Figure 2 (a). The cathode temperature was measured using a Raytek MR1SC pyrometer. The focal length of the pyrometer–cathode was 300 mm (Figure 2 (a)), which made it possible to obtain a minimum spot equal to 3.3 – 3.5 mm. The working surface of the cathode was 4.2 mm. With this spot size, the temperature measurement area was completely on the surface of the heated cathode. The sight was used to align the measurement spot of the pyrometer with the working surface of the cathode (Figure 2 (c)). The cathode temperature was measured in a monochromatic pyrometer operating mode. The emissivity of the measured surface of the LaB6 cathode was set in the range from 0.69 to 0.7 depending on the measured temperature. For the pyrometer to access the full surface of the cathode through the beam guide, the hole in the anode was drilled to a diameter of 3.5 mm; the factory hole diameter is 3 mm.

To register the signal from the thermocouple on the gun body, as well as from the source of the bombardment and heating unit, the ACTest Pro measurement automation complex was used. The complex of measurements consisted of a workstation (crate) with 4 oscillographic ADC modules LTR 210, a signal conditioning unit based on signal normalizers with galvanic isolation Dataforth 8B50–01, a software module for automation and measurements "ACTest Pro". The matching block was used to amplify the signal from the thermocouple to the required level for the ADC module. To suppress the high-frequency noise of the high-voltage inverter of the electron–beam setup, a passive U–shaped low-pass filter was used.

In the study, the recorded parameters were:
- gun body temperature, °C;
- temperature of the cathode surface, °C;
- bombardment voltage, V;
- bombardment current, mA.

The variable parameters in the study were:
- power of heating the cathode;
- heating time of the cathode;
- coolant flow.

Before carrying out the study, the vacuum chamber, in which the pyrometer was located, was evacuated to a working vacuum with a residual pressure of $5 \times 10^{-4}$ mm. rt. Art. A vacuum was also created in the accelerating gap of the gun, with a residual pressure of $7.5 \times 10^{-6}$ mm. rt. Art. The power of heating the cathode was varied by changing the bombardment current, the bombardment voltage was constant and equal to 1000 V. The bombardment current varied from 20 mA to 35 mA with a step of 5 mA. This range is valid for the ELA–15 electron gun.
To study the effect of the heating time, we chose two time intervals for heating the cathode: 30 minutes and 60 minutes or more. The first time period is the most common mode of operation of the cannon. This mode is used for welding one product with a seam length of up to 500 mm. This segment includes the following stages: heating the cathode, working out the welding mode, welding and cooling.

Figure 2 – Experimental stand for assessing the thermal state of an electron gun: (a) – diagram of the experimental stand; (b) – experimental stand (pyrometer installation); (c) – heated cathode in the lens of the pyrometer; (d) – power unit control system ELA–15I and data collection system; 1 – electron gun; 2 – cathode; 3 – pyrometer; 4 – direction of measurement of the pyrometer; 5 – place of thermocouple installation; 6 – pyrometer sight; 7 – powerball control system; 8 – data acquisition system ACTest Pro.
the cathode. The second time period is typical for mass production, when several seams with a short length or one seam with a long length are welded in one heating of the cathode.

To assess the heat load of the gun from the point of view of the coolant flow through the tubular cooler, two modes were chosen: with a flow of 1 liter per minute and without a flow. The first mode is regulated by the technical requirements for the operation of the welding electron gun. The second mode is emergency.

3. Results

As a result of the research carried out, graphs of changes in the temperature of the gun body and cathode over time were obtained for various modes of heating the cathode. Table 1 shows the modes of heating the cathode of the ELA–15 welding electron gun.

| No | Cathode heating power (W) | Duration of heating the cathode (min) | Coolant flow (liter × min⁻¹) | Figure number |
|----|--------------------------|-------------------------------------|----------------------------|---------------|
| 1  | 20                       | 30                                  | 0                          | 3 (a)         |
| 2  | 25                       | 30                                  | 0                          | 3 (b)         |
| 3  | 30                       | 30                                  | 0                          | 3 (c)         |
| 4  | 35                       | 30                                  | 0                          | 3 (d)         |
| 5  | 30                       | 62                                  | 0                          | 4 (a)         |
| 6  | 35                       | 320                                 | 1 (0)⁺                  | 4 (b)         |

⁺ At 255 minutes, the water cooling of the cathode unit of the gun was turned off

Based on the obtained dependences (Figure 3), at short–term operating modes of the gun (30 minutes), there is no significant change in the temperature of the gun body. In all modes of operation, the temperature increased on average by 2 – 3 °C from the initial temperature of the gun body. The maximum temperature rise was 3.6 °C (Figure 3 (b)). For most modes, the temperature reached the peak within 75 minutes after the start of the cathode heating. The temperature peak itself was outside the heating interval. The time interval between turning on the heating of the cathode and the beginning of the rise in the temperature of the gun body was 10–15 minutes.

In the heating mode No. 5 (Figure 4 (a)), emergency shutdown of the cathode heating was triggered by the temperature of the gun body. At 62 minutes of heating, the maximum permissible temperature of the gun body was reached, which was 30 °C. The control system of the electron gun automatically turned off the heating of the cathode. After turning off the heating for 15 minutes, a further rise in temperature was observed, the peak value was 31.1 °C.

Heating mode # 6 (Figure 4 (b)) is the normal operating mode of the electron gun. The heating power of 35 W provides with a margin the necessary cathode heating temperature to obtain the maximum electron beam current. With this heating power, the electron beam current will be limited by the accelerating voltage source. The coolant flow rate was 1 liter per minute. The duration of the regular mode was 255 minutes. During this time, the temperature of the gun increased by 2.5 °C, reaching the peak value occurred after 90 minutes after turning on the heating, after 90 minutes the temperature was stable. The increase in the gun temperature occurred 15 minutes after the heating was switched on, which is typical for all investigated modes. After 255 minutes of normal operation, the cooling of the cathode assembly was turned off. After switching off the cooling, an instantaneous rise in temperature was observed. The operating temperature limit was reached at 315 minutes of operation, 60 minutes after the cooling was turned off. The temperature rise was 6.5 °C.
Figure 3 – Dependences of the change in the temperature of the gun body on the heating mode of the cathode: 1 – the temperature of the gun body; 2 – the power of the bombing.
Figure 4 – Dependences of the change in the temperature of the gun body on the heating mode of the cathode: 1 – temperature of the gun body; 2 – bombing power; 3 – the moment of switching off the cooling of the cathode unit of the gun.

The temperature of the cathode surface at modes No. 2, No. 3, No. 4 and No. 5 was stable throughout the operation. Table 2 shows the average values of the cathode temperatures. Figure 5 (a) shows the dependence of the change in the cathode temperature in mode 2. The graph has 3 characteristic sections: a section for heating the cathode to the operating temperature, a stationary section and a section for cooling the cathode. As can be seen from Figure 5 (b), the fluctuations in the cathode temperature measured by the pyrometer are directly related to the fluctuations in the bombardment power.

| Table 2. Cathode surface temperature. |
|---------------------------------------|
| Mode number from table 1 | Average temperature of the cathode surface, °C |
| 1                      | 1408                        |
| 2                      | 1450                        |
| 3                      | 1534                        |
| 4                      | 1618                        |
| 5                      | 1510                        |
| 6                      | 1573                        |

At modes No. 1 and No. 6, a decrease in temperature was observed in the stationary heating section. So, for mode No. 6, the maximum cathode temperature was 1625°C at the beginning of the stationary section, at the end of the section the temperature dropped to 1535°C. The decrease in temperature is not associated with a change in the energy parameters of the bombardment. As can be seen from the graph...
in Figure 4 (b), the bombardment power for mode No. 6 throughout the entire section is at the level of 35 W, and characteristic fluctuations in the power and temperature of the cathode are also observed. The main reason for the decrease in the measured temperature is most likely the inaccuracy of the pyrometer measurement.

Figure 5 – Dependence of the cathode temperature change in mode 3: a – general view; b – stationary heating mode; c – cathode cooling section after heating is turned off; 1 – cathode temperature; 2 – bombing power; 3 – line of the approximating function.

For verification of the thermal model, it is most convenient to use sections of natural cooling of the cathode. Figure 5 (c) shows a graph of the change in the cathode temperature immediately after the bombardment is turned off. The time interval over which it is possible to measure the cathode temperature was 19 s. During this time, the cathode temperature dropped by 450 °C. The resulting set of points is well approximated by a power law.

4. Conclusions
As a result of the studies carried out, it was revealed that for short–term operating modes of the ELA–15 electron–beam gun, it is possible not to use forced water cooling of the gun. When the gun is in operation for more than 60 minutes, the body temperature in all modes begins to exceed the set threshold of 30 °C. With forced water cooling, the temperature of the gun body rises by 2 – 3 °C within 75 minutes and stabilizes. This makes it possible to use the gun for a long time. In the event of an emergency shutdown of the water, the gun remains operational for 30–60 minutes.
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