PECULIARITIES OF MODELING THE ANODE PROCESSES USING SG-100 PLASMATRON AS A CASE STUDY

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الملخص:
النموذج الرياضي لغمد الأنود للبلازماترون قيد الدراسة، يمكن من التنبؤ بنقاط الربط للقوس الكهربائي وتحديد أماكن التعرية الأكبر لمادة الأنود. ان أنماط متساوي الحرارة والتدفق، على التوالي، التي تم الحصول عليها من النماذج حيث كانت درجة الحرارة القصوى 32000 كلفن والسرعة القصوى على المحور في تيار الكاثود النفاث كانت 1800 م / ث، والتي اتفقت بشكل مرضٍ مع نتائج المؤلفين الآخرين. كما اتضح أن حركة البقعة القوسية على طول سطح الأنود تؤثر بشكل كبير على نمط التدفق، الأمر الذي يتطلب بحثًا إضافيًا ووصفًا أكثر تفصيلاً لأغلفة القطب، حيث طبيعة تدفق الغاز البارد والعمليات الفيزيائية المرتبطة بانحراف البلازما الكبير من التوازن الديناميكي الحراري المحلي له تأثير كبير على الارتباط.

Abstract. The article considers the peculiarities of gas flow in the plasmtron channel, taking into account the influence of the nature of the attachment of the electric arc to the wall of the plasmtron channel. The mathematical model based on the magnetic dynamic description of plasma as a continuous medium is based on the basis of gas dynamics equations, Maxwell's equations, and thermodynamic parameter relationships in ionized gas. The electrode processes were traced using a highly conductive layer corresponding to an electron temperature of 14,000 K. The model was found to be qualitatively consistent with the available data and suitable for numerical experiments.

Key words: plasmatron; cathode; anode; electrode; plasma; electric arc; electrode sheath.

Introduction

Processes occurring in the electrode sheathes of electric arcs make an insignificant contribution to the value of heat loss in the walls of the arc chamber and, at the same time, play a crucial part in the process of electrode material destruction, i.e. determine the operational life of the plasmatron. Increasing the power of electric arc plasma generators, required by industry and technology, as a rule, entails an increase in current, which, in its turn, increases the wear of the electrode material, reducing their operational life. Therefore, the study of processes of interaction of arc with electrodes is a necessary step in the design of equipment. One of the most important tasks in the studied problem area is to increase the operational life of the most critical component of the plasmatron, namely electrodes. Their erosion is determined by evaporation processes, chemical interaction of materials with plasma, diffusion of impurities, loss of mechanical strength, etc. Reliable continuous operation of modern electrodes is limited to a few dozens of hours at the chemical aggressiveness of plasma-forming gas (often oxygen-containing) and the current range 100...750 A common to industrial devices. Modes of protective and plasma-forming gas supply should provide a certain composition of the atmosphere near the emitting surface and mobility of arc root on the electrode surface in order to avoid their local overheating and melting.

Therefore, the study of the arc binding modes to the electrode surface and the speed of its movement is a crucial task.

Purpose

To obtain a mathematical model of the anode sheath of the plasmatron under study, making it possible to predict the binding points of the electric arc and to determine the places of the greatest erosion of the anode material.

Research methodology

The study of anode processes, first of all, is connected with the necessity to track the mechanism of oxygen-containing gases penetration into the cathode sheath. Binding to the anode surface and displacement of the electric arc support spot can have a significant influence on the character of gas flow [1].

As an object of the study, it was chosen the geometry of SG-100 plasmatron for sputtering with a tungsten rod cathode and a water-cooled copper anode (Fig. 1). The simulation was performed for a flow rate of 60 l/min for different values of current. The working gas was argon. The computational region is a hexagonal mesh (Fig. 2) with element sizes in the near-wall regions of 0.1 mm assigned on the basis of the work recommendations [2].

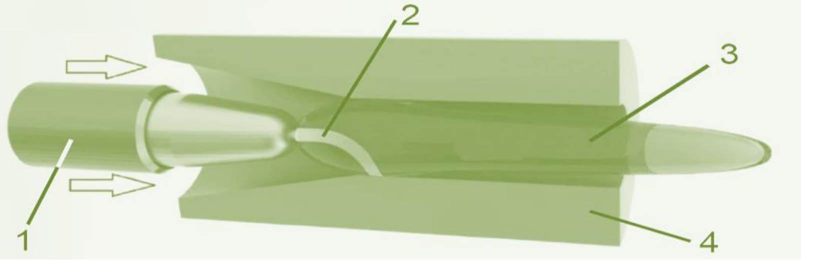


Figure 1 – Schematic model of SG-100 plasmatron
1 – cathode; 2 – electric arc; 3 – plasma jet; 4 – anode

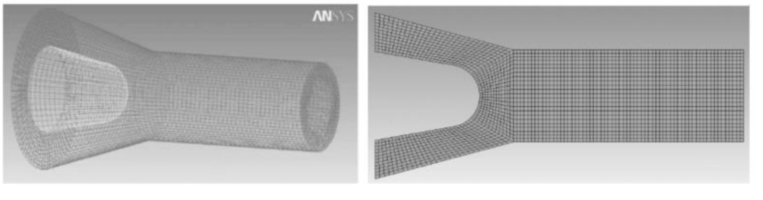


Figure 2 – Finite-element mesh of the model

The cathode surface was given a current load, and the temperature distribution in the form of dependences [1, 3]:

$$j_{cathtip} = j_0 \exp\left(-\left(r/r_c\right)^{n_c}\right), \quad (1)$$

$$T_{cathtip} = 500[K] + 3000[K]\exp\left(-\left(r/2r_c\right)^{n_c}\right), \quad (2)$$

where n_c = 4; r_c = 0,91224 mm; j_0 – emission current density, j_0 = $2{,}5{\cdot}10^8$ A/m^2, which corresponds to the current 600 A; r – distance from the cathode axis.

The calculations results are shown in Fig. 3, 4.

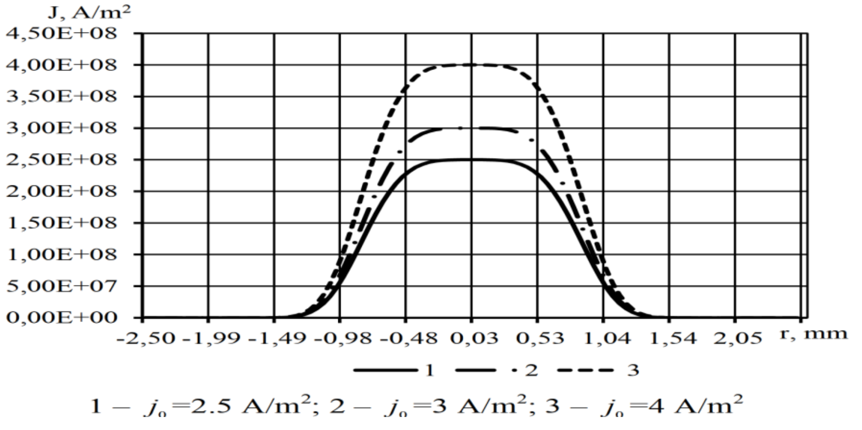


Figure 3 –Current dependence density on the distance to the cathode axis

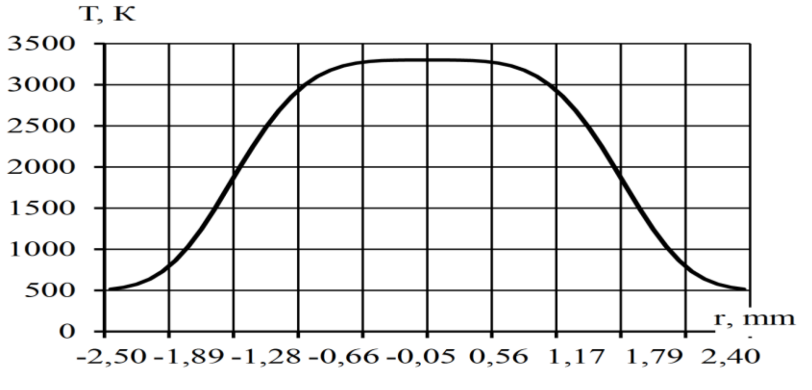


Figure 4 –Temperature dependence on the distance to the cathode axis

Heat conductivity coefficient h_w $=1{\cdot}10^5$ W/(m2K) and relative coolant temperature 500 K were set for the anode surface.

There are several options for modeling the process of binding the arc to the anode surface. When considering plasma in LTE (local thermodynamic equilibrium), the temperature near the channel walls is low, due to which the gas is non-conductive. In the work [4], the arc binding to the anode wall occurs when the following condition is fulfilled:

$$E \cdot n_{a,\,max} = E_{n,\,max} > E_b \qquad (3)$$

When the local value of electric field strength E_n in the direction of the normal to the anode surface n_a exceeds some given value E_b, the arc axis is shorted to the anode surface by a cylinder built along the normal to the surface. Inside the cylinder, the conductivity value changes according to the expression:

$$\sigma \leftarrow \max(\sigma, \sigma_b),\ s \_\ \max(s, s_b), \qquad (4)$$

where s_b – artificially high conductivity;
s – plasma conductivity.

The simpler approach for modeling the binding of the arc to the anode wall is to uprate the temperature for the near-wall layer to values that provide sufficient conductivity for binding. However, this approach strongly distorts the near-wall flow and leads to the instability of the computational procedure.

In the work [5], it was proposed to calculate the gas conductivity values based not on the equilibrium temperature values but on the electric field strength and electronic temperature values, which was calculated using the following dependence:

$$\frac{T_e - T}{T_e} = \frac{3\pi}{32} \cdot \frac{m_h}{m_e}\left(\frac{e\lambda_e |E|}{\left(\frac{3}{2}\right)kT_e}\right), \qquad (5)$$

where T_e – electron temperature; T – gas temperature; k – Boltzmann constant; m_e – electron mass; e – electron charge; λ_e – Compton length of the electron.

The results of calculations of the electron temperature for different values of the electric field strength are shown in Fig. 5.

As the electric field strength increases, the difference between the gas temperature and the electronic component becomes considerable.

Using the electric conductivity function (Fig. 6) obtained for different ratios of equilibrium and electronic temperature, the near-wall layer was modeled, which at certain values of electric field strength became electrically conductive, thus creating prerequisites for the binding of the electric arc.

However, the result obtained (Fig. 7) showed a significant discrepancy with the experimental data.

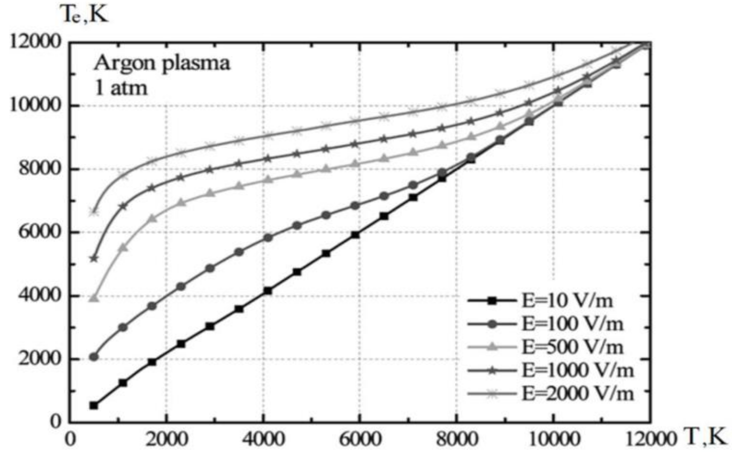


Figure 5 – Correlation of the electron temperature and the gas temperature for different values of the electric field strength

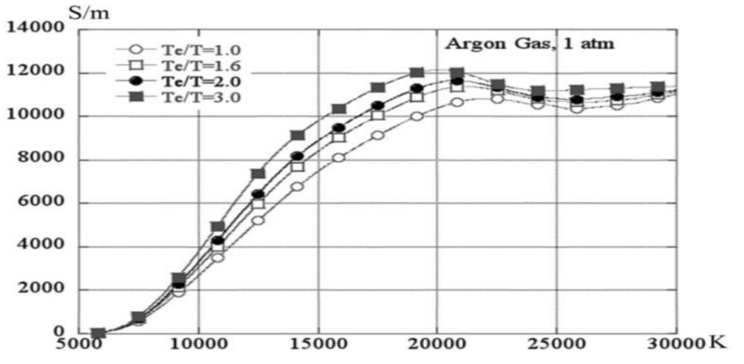


Figure 6 – Dependence of conductivity on nominal electron temperature for different correlations of the electron temperature to the gas temperature

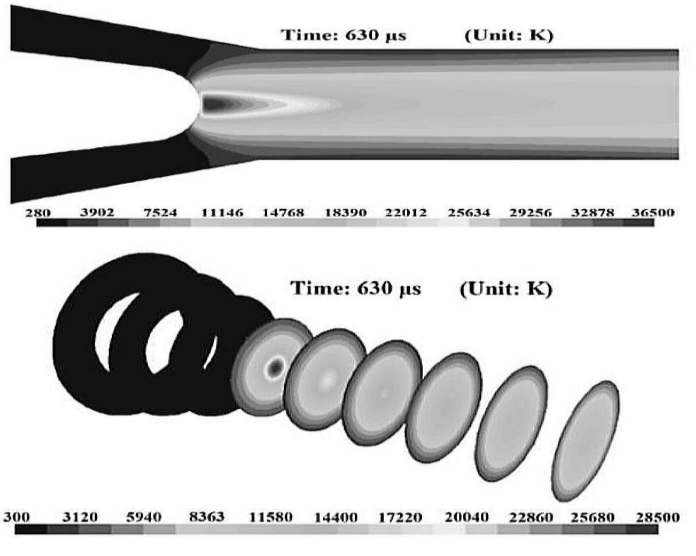


Figure 7 – Sectional temperature distribution along the plasmatron channel

In this work, the modeling of the anode layer was performed using a layer with high electrical conductivity using the solution [6, 7] for the two-temperature model, the layer thickness was set to 0.1 mm, and the electrical conductivity value was 8000 $(\text{Ohm}\cdot\text{m})^{-1}$, which corresponds to the electronic temperature of 14000 K.

The anode layer was isolated using the Heaviside function:

$$H_a(x) = \begin{cases} 0, x < 0, \\ a, x = 0, \\ 1, x > 0. \end{cases} \tag{6}$$

The mathematical description was based on the magnetogasdynamic approach to plasma as a continuous medium based on gas dynamics equations, Maxwell equations and relations for thermodynamic parameters in ionized gas.

The model was written taking into account the following assumptions:

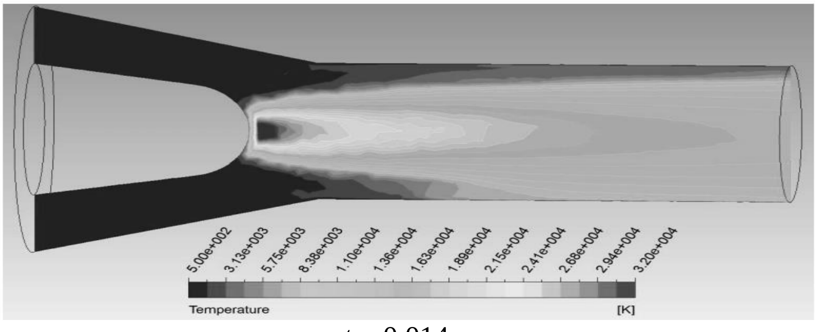
- The plasma is assumed to be quasi-neutral: $n_e = n_i$ or $n_e = \Sigma (Z_a n_a)_a$ in the case of multicharged ions or multicomponent plasma. Here n_e, n_i are concentrations of electrons and ions, respectively.
- The plasma is thermally equilibrium – the temperature of all groups of particles is the same.
- In plasma, Ohm's law is valid in its simplest form: $j = \sigma \bar{E}$.
- The expression for pressure can be written as the sum of pressures of individual components: $p = \Sigma_a n_a k T_a + n_e k T_e$.

The model is based on the classical system of Navier-Stokes equations enhanced by the system of Maxwell equations:

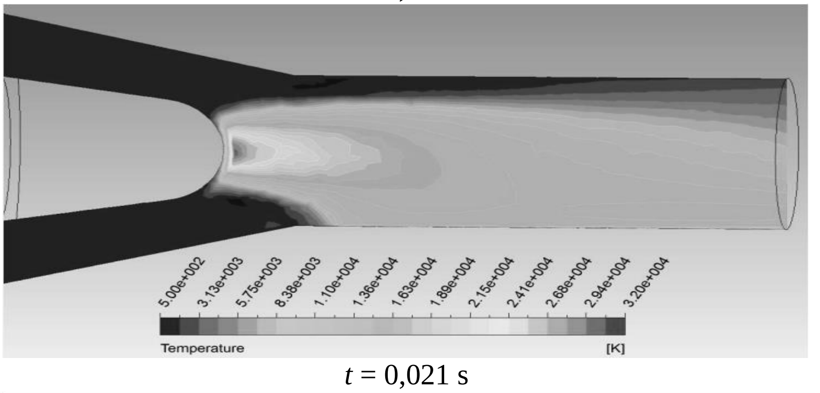
$$\begin{gathered} \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0, \\ \rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u}\right) = -\nabla \rho - \nabla \vec{\tau} + \vec{j} \times \vec{B}, \\ \rho C_p\left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T\right) = \nabla \cdot (k \nabla T) + \vec{j} \cdot \left(\vec{E} + \vec{u} \times \vec{B}\right) - 4\pi\varepsilon_r + \frac{5k_B}{e} \vec{j} \cdot \nabla T + \frac{Dp}{Dt}, \\ \nabla \cdot (\sigma \nabla \varphi) = 0, \\ \nabla^2 \vec{A} = -\mu_0 \vec{j}. \end{gathered} \tag{7}$$

Results and discussion

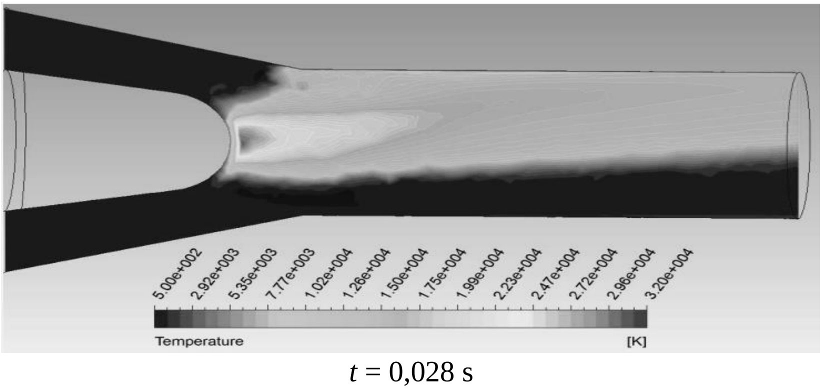
Figs. 8 and 9 show the patterns of isotherms and flow, respectively, obtained from the modeling. The maximum temperature was 32000 K and the maximum on-axis velocity in the cathode jet was 1800 m/s, which agreed satisfactorily with the results of other authors.



t = 0,014 s

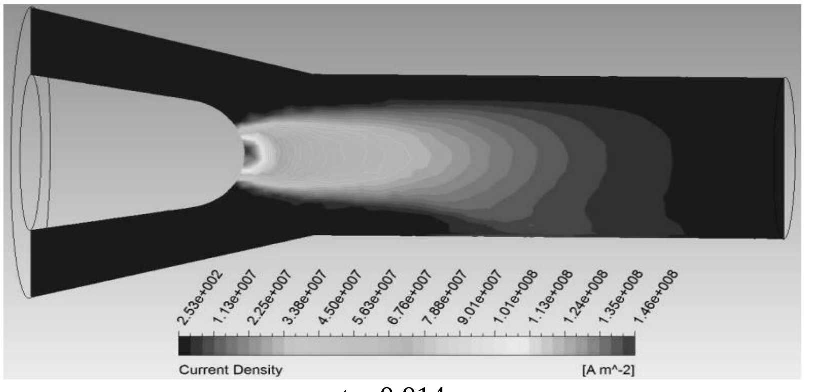


t = 0,021 s



t = 0,028 s

Figure 8 – Temperature distribution at time point *t*



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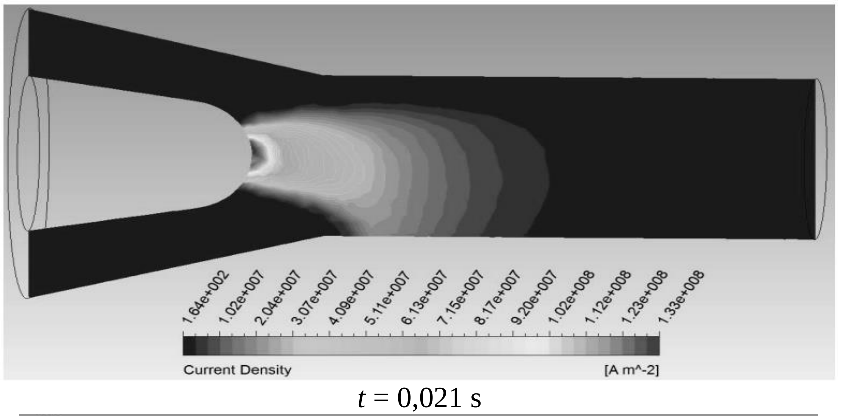
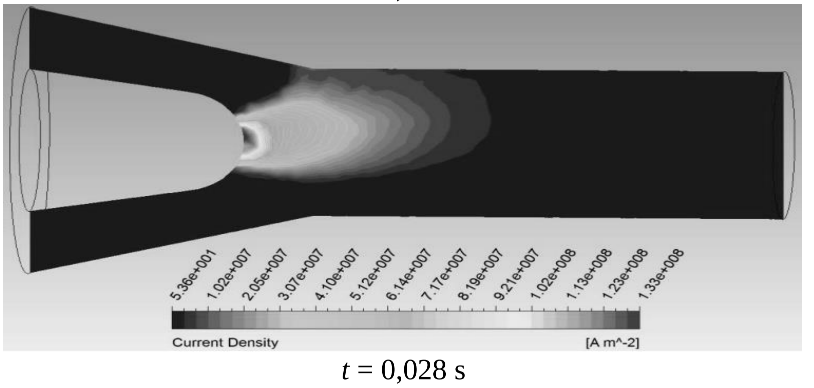


t = 0,021 s



t = 0,028 s

Figure 9 – Picture of the current density distribution at time point *t*

It was shown that the movement of the arc spot along the anode surface significantly affects the flow pattern, which requires additional research and more detailed description of the electrode sheaths, where the character of the cold gas flow and the physical processes associated with significant plasma deviation from the local thermodynamic equilibrium have a significant influence on the binding.

The character of electric arc binding has a significant influence on the flow inside the plasmatron channel. The description of internal flows for plasma equipment requires the use of linear turbulence models with corrections to describe swirling flows or more advanced hybrid models capable also to predict separated flows common to gas-vortex stabilized arc equipment.

The calculation results qualitatively coincide with the experimental data and the results of other authors [8 - 10], which makes it possible to apply the model to study the physical processes inside the plasmatrons, as well as to predict the erosion sites at the anode surface.

Conclusions

1. The modelling results for SG-100 plasmatron for sputtering showed that the main reason for penetration of oxygen-containing gases into the cathode sheath is the movement of the arc roots on the anode surface, which contributes to the formation of back flows towards the cathode.

2.The proposed model of the anode sheath made it possible to predict the binding points of the electric arc and to determine the places of the greatest erosion of the anode material. In the course of the numerical experiment, it was found that the motion of the arc roots qualitatively coincides with the erosion places for the samples after the operational life testing.

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