تصميم الحماية الديناميكية للغاز لتجميع الكاثود باستخدام بلازماترون P-13 دراسة حالة

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الملخص :

تتناول المقالة طريقة لتصميم تجميعات الكاثــــود من البلازماترون في أنظمة CAD / CAE المتكاملة باستخدام النماذج الرياضية المقترحة في إطار النهج الديناميكي المغنطيسي باستخدام معيار نوعي لتقييم كفاءة الحماية الديناميكية للغاز. وعلى هذا النحو ، يُقترح استخدام قيمة الضغط الجزئي الذي يحدث عنده انكماش قوس كهربائي على سطح كاثود. كان التباين بين البيانات التي تم الحصول عليها 6٪ لدرجة الحرارة و 3٪ للسرعة القصوى مقارنة بالتجربة عند محاكاة قوس اللحام بالضغط الجوي

Alkeeb Ahmed M. Mohammed Aljali

DESIGN OF GAS-DYNAMIC PROTECTION OF CATHODE ASSEMBLY USING P-13 PLASMATRONAS A CASE STUDY

Article brief. The article considers a method for designing cathode assemblies of plasmatron in the integrated CAD/CAE systems using the proposed mathematical models within the framework of the magnetogasdynamic approach using a qualitative criterion for assessing the efficiency of gas-dynamic protection. As such a criterion, it is proposed to use the value of partial pressure at which contraction of an electric arc to a cathode surface occurs. The discrepancy between the obtained data was 6% for temperature and 3% for maximum speed compared with the experiment when simulating an atmospheric pressure welding arc.

Key words: plasmatron; gas-dynamic protection; cathode assembly; plasma; gas-dynamic approach; magnetogasdynamic approach.

Introduction

There are many technological processes using plasmatrons. The main purpose of plasmatron is to obtain and heat plasma flows, which are then used to heat technological materials fed into the plasma jet (powders or wires), to carry out chemical reactions in the plasma jet, or to intensively heat surfaces in the plasma stream. When heating metal surfaces, it is advisable to use not only the thermal energy of the plasma flow, but also the energy of the electrode sheath of the electric arc discharge, if the heated surface is used as an electrode. This increases the concentration of energy on the surface, and also increases efficiency of the process due to removal of part of discharge from the plasmatron, and conversion of electrode sheath energy losses into useful energy of the surface heating process. According to these features, all plasmatrons can be divided into plasmatrons with an internal arc for heating the gas flow and plasmatrons with an external arc for heating metal surfaces. The last group includes plasmatrons for plasma welding, plasma cutting of metals, metallurgical plasmatrons for melting metals in electric arc plasma furnaces, plasmatrons for plasma-mechanical processing of metals. Plasmatrons with an external arc have their own characteristic features. Plasmatrons with an internal arc are the most common, diverse and omni-purpose type of plasmatrons.

Purpose

Development of algorithm for designing cathode assemblies of electric arc plasmatron, which is based on the method for determining parameters of the gas-dynamic protection of the cathode with a qualitative and quantitative assessment of the allowable values of partial pressure of oxygen-containing gases.

Research methodology

When designing cathode assemblies, it is necessary to consider the entire plasmatron as a system for performing the main function – heating the working substance. In order to do this, internal functions must be implemented: organization of the working process in the plasmatron and ensuring operability of structure, including:

1. Formation of an electric discharge with the necessary characteristics;
2. Organization of flow of heated substance and its interaction with the discharge, providing the necessary properties of the discharge;
3. Removal of heat falling on the walls of structural elements;
4. Movement of the discharge on the electrodes, thermal conditions of the electrodes and protection of the electrodes from oxidation.

The listed functions are carried out by the corresponding subsystems of the plasmatron:

- electrical subsystem, including main and auxiliary electrodes (discharge ignition), insulators, connecting elements to power supplies;
- gas system, including devices for introducing gas into the discharge chamber, giving the gas flow in the plasmatron the required speed and direction of movement, introducing, if necessary, protective or process gas, channels for transporting gas in the plasmatron, seals, connecting devices to external systems.
- cooling system, including jackets for cooling heat-stressed structural elements, channels for organizing the flow of coolant.

The method of designing cathode assemblies is based on the algorithm for determining the key parameters of the plasmatron as a whole. The perfection of the method is determined by the accuracy of calculating the geometric parameters of the cathode assembly, the flow rates of the protective and plasma gases, which can provide the greatest resource of the equipment. The design task is as follows: to determine geometric and gas-dynamic parameters of the cathode assembly from the known values of the jet thermal power at the outlet of the plasmatron. Thermal power is calculated as follows:

$$P = h \cdot G,$$

where h is the mass average enthalpy of plasma; G is the total gas flow.

From the known values of enthalpy and gas flow, it is possible to calculate the values of the average temperature, the output velocity, and also to determine the electrical power of the plasmatron. Traditionally, the relationship between the external parameters of the plasmatron and the internal ones is determined on the basis of empirical dependencies that are obtained experimentally. However, in the proposed design method, it is supposed to apply both analytical dependencies to determine geometric parameters of the cathode assembly in the first approximation, and numerical ones. The key parameter in choosing the geometry and assigning the flow rates of the protective and plasma-forming gas is the value of partial pressure of oxygen-containing gases [1]. Therefore, in the algorithm for determining parameters of the cathode assembly (see Fig. 1), it is proposed to use several criteria for assessing effectiveness of gas-dynamic protection, namely: the quantitative criterion proposed in [2] and the qualitative one proposed in the frames of this work.

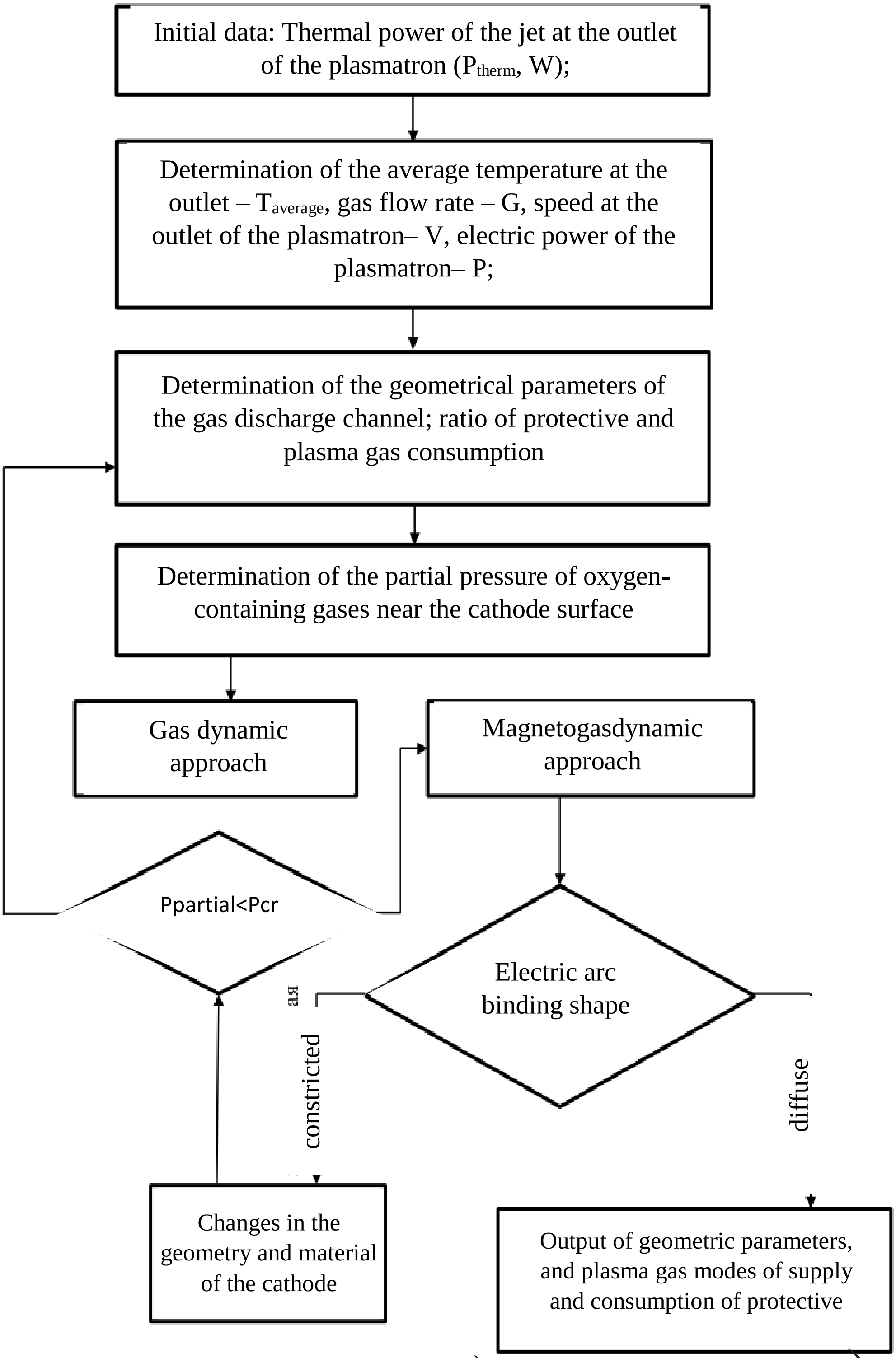
Initial data: Thermal power of the jet at the outlet of the plasmatron (P_{therm}, W);
Determination of the average temperature at the outlet – $T_{average}$, gas flow rate – G, speed at the outlet of the plasmatron– V, electric power of the plasmatron– P;
Determination of the geometrical parameters of the gas discharge channel; ratio of protective and plasma gas consumption
Determination of the partial pressure of oxygen-containing gases near the cathode surface
Gas dynamic approach
Magnetogasdynamic approach
Ppartial<Pcr
Electric arc binding shape
ая
constricted
diffuse
Changes in the geometry and material of the cathode
Output of geometric parameters, and plasma gas modes of supply and consumption of protective

Figure 1 – Algorithm for determining parameters of the cathode assembly

Here, a qualitative assessment of the mode of binding the electric arc to the surface of the hot cathode plays a decisive role, since under certain conditions the diffuse mode of binding can be realized even at emission current values of 0.7 ... 0.8 of the emission current value in vacuum.

Let us consider a numerical study of the efficiency of gas-dynamic protection of the cathode assembly of P-13 plasmatron (Fig. 2) [3] and a comparison of simulation results with experimental data. An integral step in the creation of a mathematical model is its verification with experimental data.

The plasmatron uses gas-vortex stabilization of the arc with fixation of the arc length by a ledge.

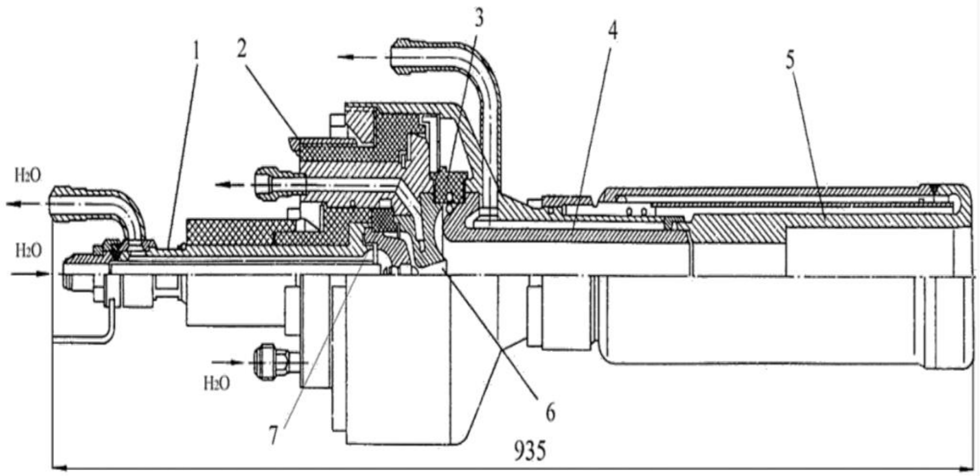

Figure 2 – Structural diagram of P-13 plasmatron:
1 – cathode assembly; 2 – housing of interelectrode fillers;
3, 7 – swirl ring; 4 – assembly of the initial part of the anode; 5 – assembly of the detachable part of the anode; 6 – interelectrode fillers

P-13 plasmatron contains a cathode assembly, a body of an interelectrode filler with an interelectrode filler, a swirl ring, assemblies of initial and detachable parts of the anode. The assembly of the interelectrode filler is a single water-cooled assembly with sealing of water and gas cavities with sealing parts, which includes a copper insert and a steel case. The sleeve-like configuration of the casing makes it possible to simplify the supply of cooling water and protective gas to the swirl ring. The interelectrode filler is made with an enlarged conical console and a conical water cavity. The housing has a cavity for the passage of cooling water, the volume of which is limited by the width of the annular recess and two sectors. Insulators and swirl rings are made of caprolon and provide electrical isolation of the interelectrode filler from the anode and cathode housings. Gaskets and rubber rings used in the assembly prevent leakage of working and protective gases into the atmosphere.

The assembly of initial part of the anode consists of a housing and a copper electrode. There are a working gas supply fitting and fittings for supplying and discharging cooling water on the housing. Unlike the cathode assembly, the initial anode assembly cannot be independently leak tested.

The assembly of the anode detachable part is a welded tubular structure with a coaxial body, a stepped copper electrode and a cooling water inlet. The sealing of connectors of detachable and initial parts of the anode is achieved by using sealing rings and glands. The main characteristics of the plasmatron are shown in Table 1.

Table 1 **Technical characteristics of P-13 plasmatron**

Type	**Power, kW**	**Arc voltage, V**	**Arc current, A**	**Protective gas onsumptio 10^{-3} kg/s**	**Type of working gas**	**Working gas consumption, 10^{-3} kg/s**	**Thermal efficiency**	**Outlet jet temperature, K**
P-13	**820**	**820**	**1000**	**0.025**	**air**	**146**	**0,8**	**3500**

To make the computational domain, it is necessary to create a solid model of the plasmatron flow path. A three-dimensional model of P-13 plasmatron assembly has been built using SolidWorks CAD program. Fig. 3 shows a solid-state model of the plasmatron with a selected computational domain.

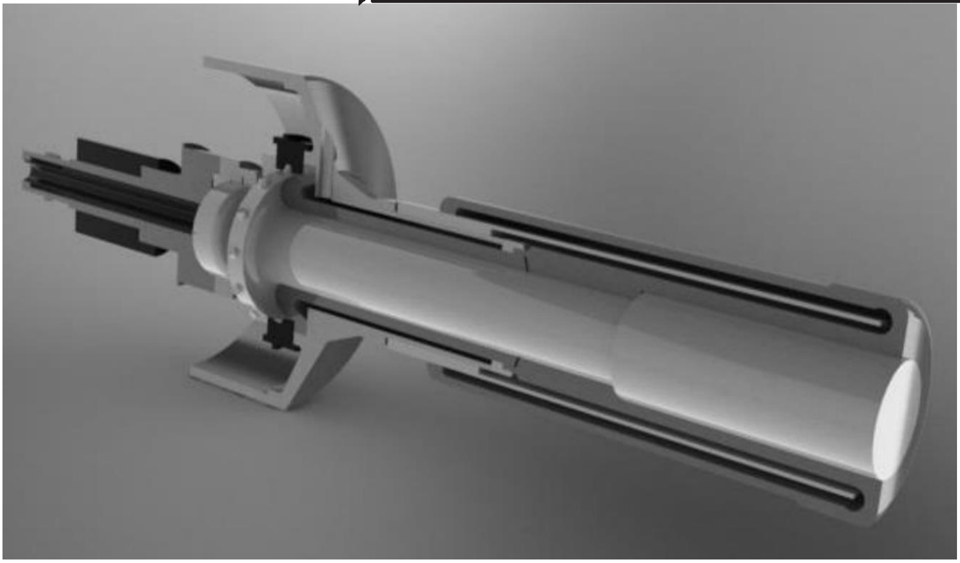

Figure 3 – Model of P-13 plasmatron made using SolidWorks

To determine the thermal state of the plasmatron structural elements, the temperature values and heat transfer coefficients on the surface of the bodies are required. These values can be obtained in the course of a full-scale experiment, however, preparation and conduct of the experiment is a labour intensive and time consuming process. An alternative way to obtain the required parameters can be a numerical experiment, when the required values are calculated during the calculation for the required operating mode of the equipment. The heat flux is determined depending on:

$$q_w = h_c \cdot (T_{wall} - T_{ref}),$$

where qw is the heat flux; h_c is the heat transfer coefficient; T_{wall} is the flow temperature on the wall; T_{ref} is the average temperature of the near-wall control volume.

The task of determining the value of the heat transfer coefficient involves two calculations: calculation of the flow, in which the wall is adiabatic; followed by calculation with a given wall temperature. Then, the values of the total flow temperature on the wall T_{ad} are taken from the first calculation, and the values of the heat flux from the wall Wall_Heat_Flux and the values of the total flow temperature on the wall Total_Temperature (T_{total}) are extracted from the second calculation. The heat transfer coefficient is determined by the formula:

$$h_c = Wall\_Heat\_Flux / (T_{total} - T_{ad}).$$

The results of blowdowns on test problems have showed the extreme sensitivity of the obtained values of the heat transfer coefficient on the number and size of elements of the computational grid. A comparative analysis of the obtained data with experimental studies has showed that the most accurate result can be obtained for a finite element mesh with a dimensionless parameter $Y^+ \approx 1$. Achieving such values is possible only with the use of structured meshes.

The discretization of the computational domain is performed using hexagonal elements in ICEM CFD environment (Fig. 4).

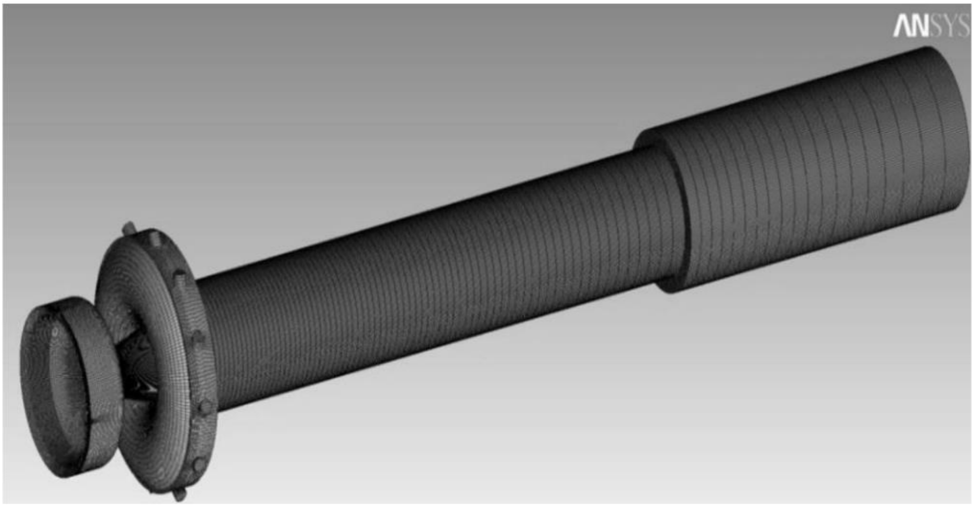

Figure 4 – Finite element mesh of the model

Pre-launch, cold blowdowns using the resulting grid with the number of elements of one million showed an unstable behavior of the computational procedure associated with the existence of zones with a difference in flow velocities by more than one order, which required the use of different time scales or a time step of $1 \cdot 10^{-6}$ s, in this case it is necessary to use powerful computing systems.

From the point of view of saving computing resources, the problem has been solved in several stages; at the first stage, swirl rings for supplying argon and air is considered in turn, and the velocity components are calculated in characteristic areas. At the next stage, the original channel geometry is replaced by a simplified one with the calculated values of velocities specified as boundary conditions. Thus, the number of elements of the computational grid of the model is reduced by 10 times, providing the value $Y^+ \approx 1 \ldots 2$.

As a result of calculations, the average value of the heat transfer coefficient $h_c = 2 \cdot 10^{-5}$ W/(m^{2}K) is determined.

The initial data for modeling is the current strength, as well as the consumption of protective and working gas. For all cases, the protective gas flow rate is taken as 0.025 kg/s, the working gas flow rate is $95 \cdot 10^{-3}$ kg/s, $135 \cdot 10^{-3}$ kg/s, $142 \cdot 10^{-3}$ kg/s. Current strength – 500A, 700A, 900A. The supply of protective and working gas is carried out through swirl rings, the geometry of which is shown in fig. 5.

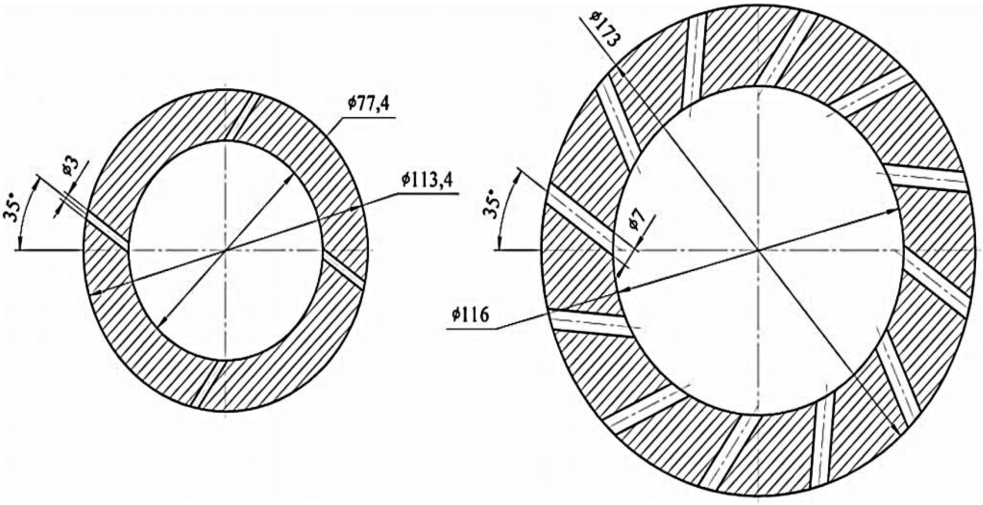

Figure 5 – Geometry of the swirl ring channels

As the initial conditions for the calculations, the result of cold blowdowns for an air flow rate of 95 g/s and argon of 0.025 g/s is taken. (Fig. 6).

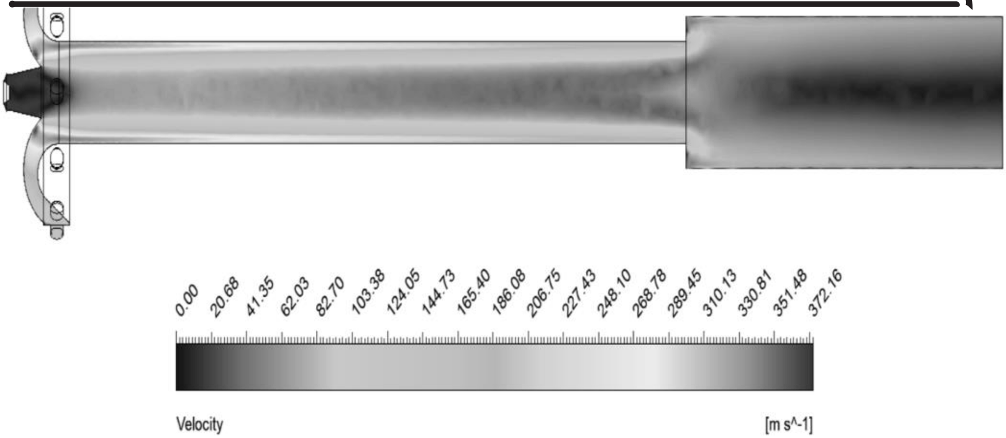

Figure 6 – Distribution pattern of flow velocities

Research results and discussion

The obtained current-voltage characteristics and the average gas temperature at the outlet of the plasmatron for various values of the flow rates of the plasma-forming gas satisfactorily fit to the experimental data (Fig. 7, 8).

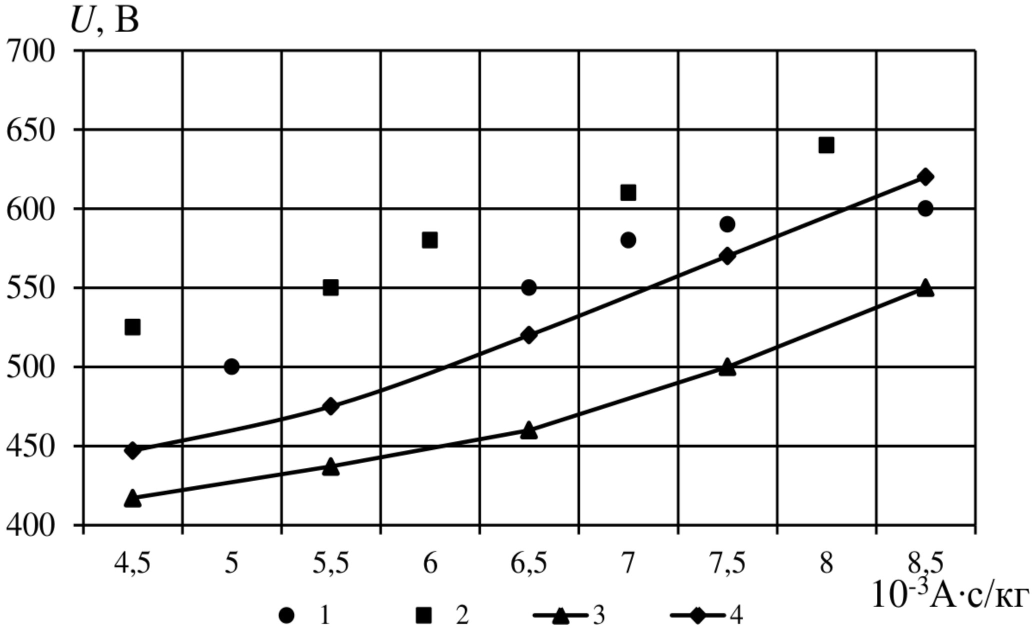

Figure 7 – Volt-ampere characteristic of P-13 plasmatron for various air flow rates: 1.3 ... 95 g/s; 2.4…100 g/s, here: 1, 2 – experimental data; 3, 4 – results of the author

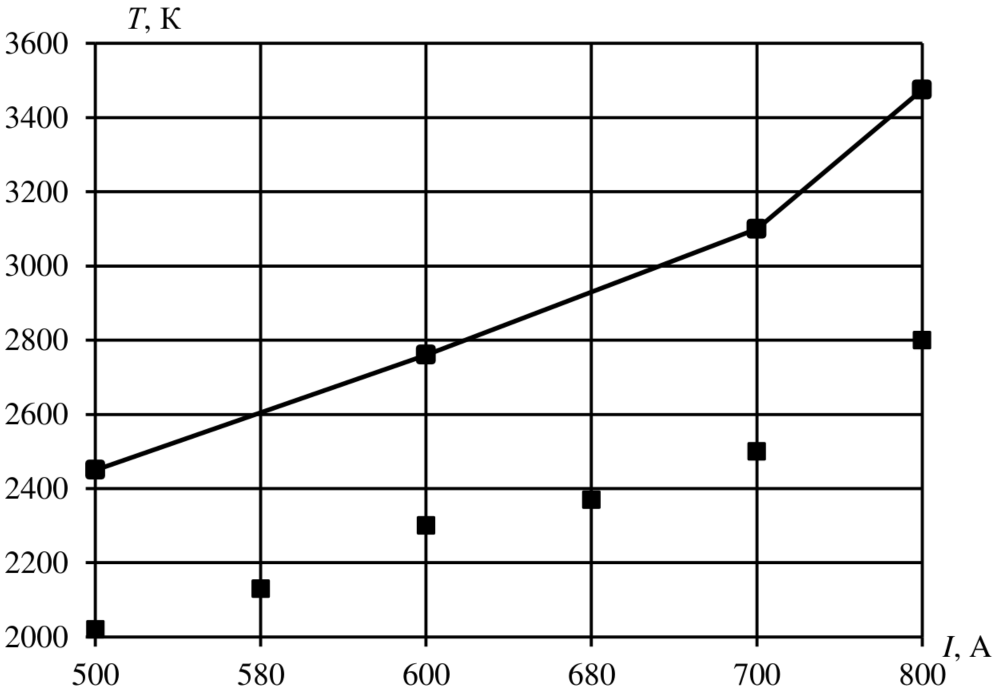

Figure 8 – Dependence of the plasmatron outlet temperature on the current strength, at an air flow rate of 95 g/s, here:
1 – results of the author; 2 – experimental data

Figures 9-11 show the temperature and velocity distribution along the plasmatron channel.

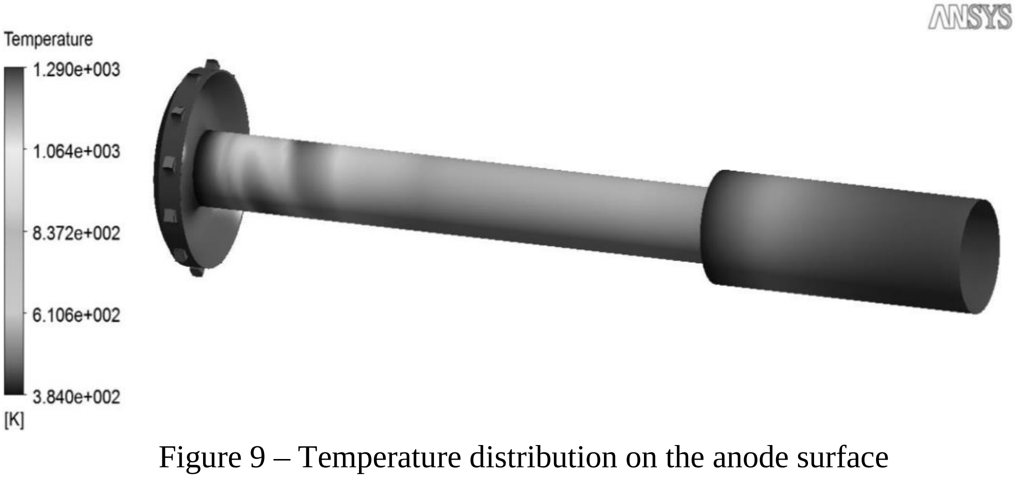

Figure 9 – Temperature distribution on the anode surface

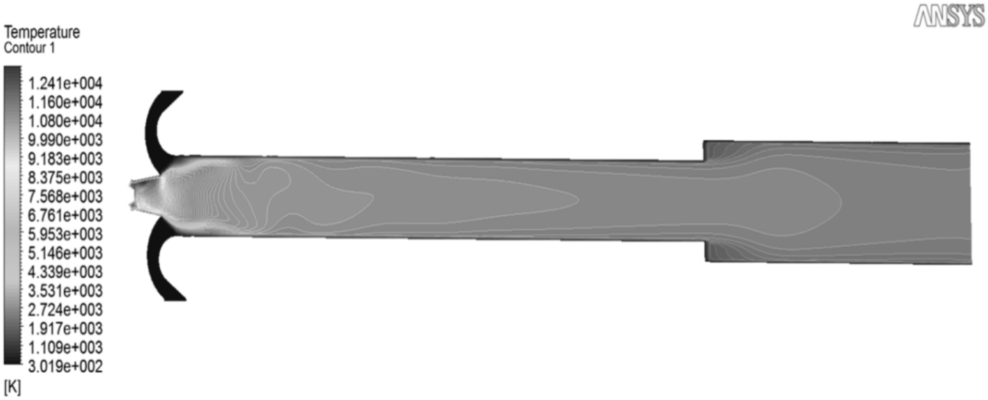

Figure 10 – Temperature distribution inside the gas discharge path

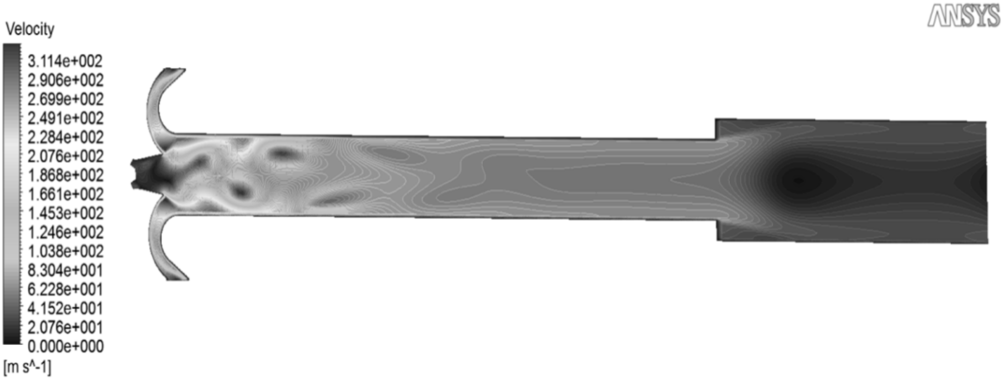

Figure 11 – Pattern of speed distribution

A large number of works [4-6] are devoted to the study of features of the gas flow in the channel of the cathode assembly of plasmatron. Their goal is to determine the influence of geometry of the cathode assembly on the gas dynamics of flow in the discharge channel, which determines the composition of atmosphere in the near-cathode area and, as a consequence, performance of the cathode assembly as a whole. In the work [7] during cold blowdowns of the sectioned assembly model, to establish the nature of the gas flow in the vortex chamber, the probe method has been used to measure the static pressure. According to the results of measurements, it is suggested that the reason for penetration of aggressive working gas to the hot cathode is radial pressure fluctuations in the vortex chamber. In the work [8-10], it is performed numerical simulation of the gas flow in the channel of the cathode assembly and it is determined the composition of atmosphere in the near-cathode area. The results of the above works can be used only at the stages of pre-launch blowdowns, since they exclude the presence of an intense heat source, which can be considered an electric arc.

Partial pressure calculations have been carried out for an argon flow rate of 0.025 g/s and an air flow rate of 95 g/s; modeling has been carried out within the frames of the gas-dynamic and magnetogasdynamic approaches. Fig. 12 shows the calculation results for two cases.

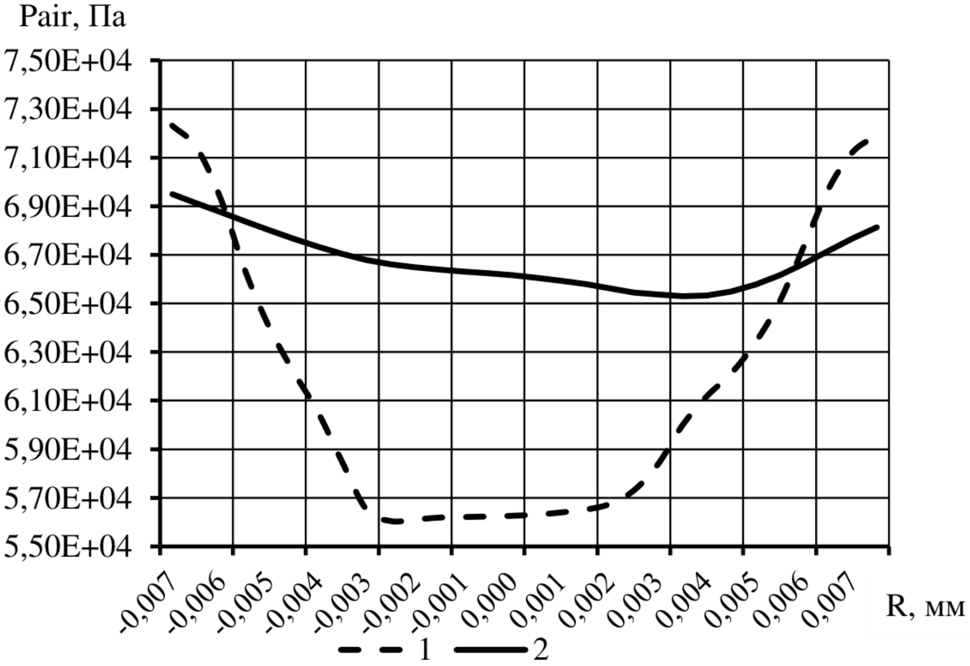

Figure 12 – Partial air pressure at the cathode section:
1 – gas dynamic approach; 2 – magnetogasdynamic approach

Small differences in the results can be explained by achieving the limit in relation to the perfection of geometric parameters of the cathode assembly. Reducing the harmful effects of oxygen-containing gases is possible only by increasing the consumption of protective gas, the use of cathode materials with a higher poisoning threshold, which include lanthanum hexaboride, iridium-lanthanum and iridium-tungsten emitters. There has recently been increasingly frequent usage of composite cathodes with oxygen-absorbing inserts in modern plasmatrons. However, from the point of view of ensuring the maximum service life of plasma equipment, it is most rational to use combined devices that include a typical linear plasmatron with a cold hollow cathode and an auxiliary induction plasmatron, which serves to axially supply hot gas to the cathode cavity to create favorable conditions for diffuse coupling of electrical arcs. In this case, the need to use a protective gaseous medium is eliminated, and operation of the plasmatron in the diffuse mode eliminates the possibility of burning the cathode walls.

Conclusions

1. It is proposed an algorithm for designing cathode assemblies of electric arc plasmatron, which is based on the developed method for determining parameters of the gas-dynamic protection of the cathode with a qualitative and quantitative assessment of allowable values of partial pressure of oxygen-containing gases.

2. It is made a comparative analysis of the results of numerical simulation with the results of experimental studies of P-13 plasmatron. The numerically obtained current-voltage characteristics, as well as the values of the average flow temperature, fit satisfactorily to the experimental data. The calculation error is 19% for the current-voltage characteristic of the arc and 20% for the average flow temperature at the outlet of the plasmatron.

3. It is carried out an estimate of parameters of the gaseous medium in the near-cathode area of the plasmatron. The partial air pressure according to the calculation results is $7 \cdot 10^4$ Pa, the obtained value exceeds the poisoning threshold for all known materials.

4. It is proposed as recommendations for solving the problems of gas-dynamic protection, the use of new materials based on compositions of lanthanum hexaboride, iridium-lanthanum and iridium-tungsten, which are less sensitive to poisoning. Mathematical modeling has shown the prospect of using a combined plasma cathode assembly that ensures the cathode performance even when operating on oxygen-containing gases.

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