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THE RESEARCH INTO THERMAL AND ENERGY CHARACTERISTICS OF A PLASMATRON FOR OBTAINING HYDROGEN LOW TEMPERATURE PLASMA

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Abstract

The article presents the results of experimental research of voltampere characteristics, thermal fluxes into the plasmatron elements, electrode erosion, thermal efficiency of a hydrogen plasmatron in the wide range of parameters. Has been developed an original construction of a plasmatron for obtaining hydrogen low-temperature plasma.

Key words: plasmatron, hydrogen, cathode, voltampere characteristic, heat flux, electrode.

ИССЛЕДОВАНИЕ ТЕПЛОВЫХ И ЭНЕРГЕТИЧЕСКИХ ХАРАКТЕРИСТИК ПЛАЗМОТРОНА ДЛЯ ПОЛУЧЕНИЯ ВОДОРОДНОЙ НИЗКОТЕМПЕРАТУРНОЙ ПЛАЗМЫ

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Реферат

В статье представлены результаты экспериментальных исследований вольтамперных характеристик, тепловых потоков в элементы плазмотрона, эрозии электродов, теплового КПД водородного плазмотрона в широком диапазоне параметров. Разработана оригинальная конструкция плазмотрона для получения водородной низкотемпературной плазмы.

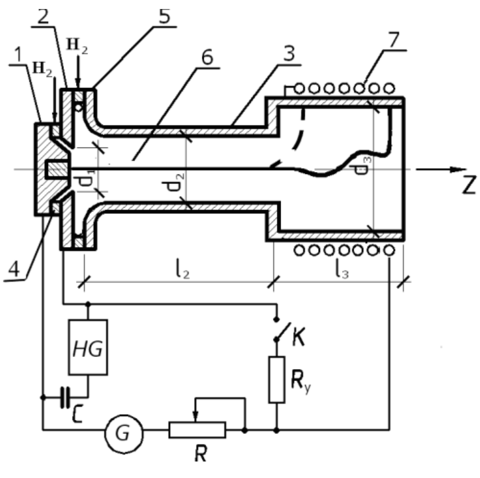
Ключевые слова: плазмотрон, водород, катод, вольт-амперная характеристика, тепловой поток, электрод.

Introduction

Currently, economically effective processes for the combined production of acetylene and ethylene from hydrocarbon raw materials, plasma-chemical processing of waste from various industries, etc. are widely used. Especially promising are considered the processes of using low-temperature hydrogen plasma [1–16]. In processes where combustion gases are used to supply energy, the efficiency of energy use is very low due to the fact that due to the presence of oxygen in the working mixture, a significant amount of resinous polymers is formed. This reduces the yield of target products and complicates the subsequent processing of gas cracking. These disadvantages can be eliminated if hydrogen heated to a temperature of (3000–4000) K is used as a coolant for pyrolysis of hydrocarbons. A DC or AC plasmatron of the required power can act as a hydrogen plasma generator [3, 4, 6–8]. The increase in the power and service life of such plasmatrons is largely determined by the success in the study of the thermal characteristics and erosion of electrodes. The following works are devoted to this kind of research [3–5, 9, 12–15, 17–20]. Cathode erosion occurs due to complex thermal, electrical, chemical and mechanical processes in the near-electrode area. The main emphasis in most studies of this problem is made on the experimental study of phenomena and empirical generalization of experimental data in order to create a substantiated mathematical model in the future and find rational methods for calculating the optimal designs of cathodes. It is known that the main factor determining the rate of erosion is the specific heat flux into the cathode [12–14, 17–19]. For thermionic electrodes, as a rule, it exceeds 50 kW/sm^2 and depends on the type of working gas, current strength, the nature of the electrode cooling, and other factors. If the arc burns in hydrogen, then the specific heat flux due to the high thermal conductivity of this gas is especially high, therefore, studies of heat fluxes into the elements of the plasmatron and the erosion of electrodes are relevant.

Description of the installation

The diagram of the plasmatron, its power supply and arc ignition are shown in Figure 1. The main elements of the plasmatron are the cathode (1), the igniting electrode (2) and the stepped anode (3). The cathode is made of a 10 mm long thoriated tungsten rod, soldered flush into a copper ring. Tungsten rods (3–10) mm in diameter were used in the experiments. The ignition electrode is made of copper in the form of a washer section with an inner diameter of d_1 = 16 mm. The tested copper stepped anodes had diameters d_2 = 8 mm and d_3 = 16 mm, length l_2 = (30–50) mm. The anode length $l = l_2 + l_3$ varied from 90 mm to 150 mm. To reduce the erosion of the working surface of the anode, a solenoid wound from a copper tube (7) is installed. The axial magnetic field created by it (0,06–0,08) T provides such speeds of rotation of the closing radial section of the arc, at which the service life of the anode exceeds 1000 hours. The cathode, igniting electrode, anode and solenoid are intensively cooled with chemically purified water, which is supplied to the plasmatron cooling system under the pressure of (10–15)×10^5 Pa. To calculate the heat fluxes into the electrodes, the temperature of the water at the inlet and outlet of the plasmatron was determined using chromel-copel thermocouples with the recording of the EMP-109AI device readings.



1 – cathode, 2 – ignition electrode, 3 – anode, 4,5 – insulators, 6 – arc, 7 – solenoid

Figure 1 – Plasmatron and power supply diagram

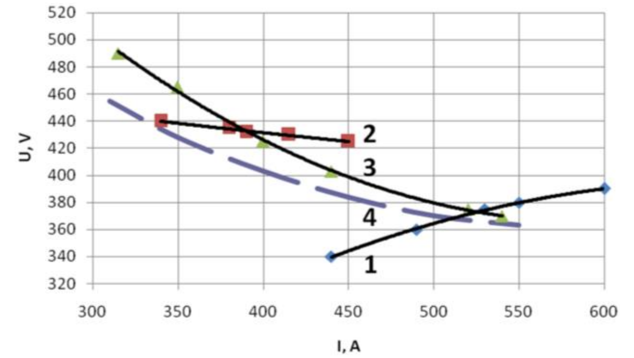
The hydrogen pressure before the flow meters at the plasma torch inlet was (4–8)×10^5 Pa. The gas consumption was measured with devices of the PV-1033 type, and its smooth adjustment was carried out by automatic devices of the DMPK-100 type. Hydrogen was fed into the gap between the cathode and the ignition electrode through two tangential holes 1,2 mm in diameter located in a twist ring with an inner diameter of 50 mm (consumption 0,1–0,2 g/s). The second swirl chamber (5), located between the ignition electrode and the anode, was supplied with gas through four tangential holes 2,4 mm in diameter located in a swirl ring with an inner diameter of 64 mm. The total hydrogen consumption varied in the range of (0,9–1,2) g/s.

The plasmatron was powered from a power source with a rated current of 600 A and a voltage of 900 V. Since its external electrical characteristic is rigid, and the voltampere characteristic of the arc is falling, a variable step ballast resistance R is connected in series with the arc (for the purpose of its sustained burning). The plasmatron was ignited using a high-voltage high-frequency oscillator with a voltage applied to the ignition electrode (3). The resistance R_y = (10–20) Om is connected between the ignition electrode and the anode through the contactor. Such a circuit for connecting the oscillator to the electric power circuit of the plasmatron made it possible to exclude the ingress of HF voltage into the power supply circuit and thereby ensured a reliable protection of the rectifier from overvoltage. Solenoid (7) is connected in the power supply circuit in series with the arc.

Research of voltampere and thermal characteristics of the plasmatron

In accordance with the methodology [1–8, 16], investigations of the electric field strength of an arc burning in hydrogen were carried out. The results of experiments on the study of voltampere characteristics confirmed the need to maintain the high tangential velocity of hydrogen swirling and a smooth (nonseparated) transition from the swirl ring to the inner diameter of the electrode for the purpose of ensuring gas-dynamically stable arc burning. In the experiments, it was also found out that the arc in the plasmatron scheme under consideration burns with lower voltage pulsations compared to an arc with a self-adjusting length which burns in a cylindrical channel without a ledge.

Figure 2 shows the voltampere characteristics of a hydrogen arc burning in a plasmatron with different anode lengths.



1 – l_2 = 30 mm; 2 – l_2 = 39 mm;
3 – l_2 = 50 mm; 4 – calculated curve
G_{H2} = 1 g/s, d_2 = 8 mm, p = 1,4×10^5 Pa

Figure 2 – Voltampere characteristics of the arc at different lengths

The experimental results showed that at a length $l_2 \leq 30$ mm, the electrical characteristic is ascending (curve 1) and at a current of less than 520 A lies below the characteristic of an arc with a self-aligning length (curve 4), calculated by the formula:

$$U = 3190\left(\frac{G}{I}\right)^{0,4}\left(\frac{G}{d}\right)^{0,3}(pd)^{0,36}, \quad (1)$$

where d – inner diameter of the anode of constant cross-section, mm.

It can be surmised that at higher current values, curve 1 coincides with curve 4 on the assumption that the mechanism of formation of the current-voltage characteristic of an arc in hydrogen for a plasmatron with a stepped output electrode is similar to a cylindrical anode.

It should be noted that in the studied range of currents at $l_2 \leq 30$ mm, the arc burns stably. Visual inspection of the inner surface of the anode showed that the arc shunting occurs only behind the ledge in the section of the electric discharge chamber with a diameter d_3. At l_2 = 50 mm, the voltampere characteristic of the arc (curve 3) practically coincides with the calculated curve 4, and the shunting zone, already near the ledge, captures some electrode surface with a diameter of d_2 = 8 mm; the electrode ledge undergoes noticeable erosion within a few hours of operation. Therefore, the length l_2 = 50 mm is more than the limiting one. With an increase in l_2 over 39 mm, the pulsation amplitudes of current and voltage increase, and the pulsation frequency also decreases. The data obtained testify to the possibility of achieving a high electrical efficiency of a plasmatron with a stepped shape of the output electrode.

Simultaneously with the study of the current-voltage characteristics of the arc, the study of heat fluxes into the elements of the plasmatron (cathode, anode and ignition electrode) was carried out. This made it possible to calculate the thermal efficiency of the plasmatron, the enthalpy and the average mass temperature of gas depending on the magnitude of the arc current, the anode length, and the methane content in hydrogen under pressure at the outlet of the plasmatron which equals 1,5×10^5 Pa.

Figure 3 shows the data on heat fluxes into the cathode when hydrogen is used as working gas.

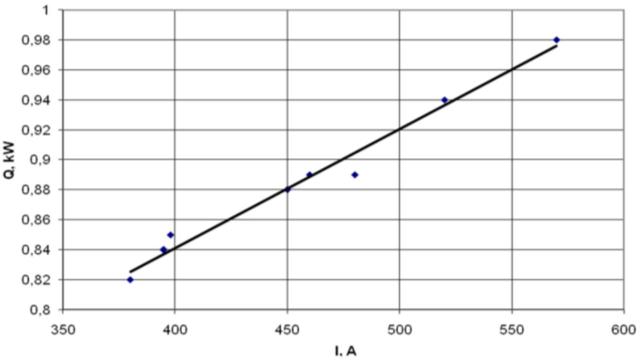


Figure 3 – Dependence of the heat flux into the cathode on the arc current in hydrogen at l_2 = 39 mm

Studies of heat fluxes into the cathode showed that when hydrogen was used as a working gas at equal currents and stable modes of arc burning (l_2 = 39 mm), they turned out to be lower than for nitrogen [15]. Somewhat unexpected results are obtained with an unstable mode (l_2 = 50 mm), when the current amplitude increases and the arc shunting frequency decreases. In this case, heat fluxes into the cathode in the range of current values under consideration increase by about 2 times (Figure 3). This is reflected in the rate of erosion of both the cathode and the anode.

Rapid destruction of the cathode in a hydrogen environment was found during the operation of the plasmatron in the non-self-sustained combustion mode, when the current pulsations reached a noticeable value, although the absolute value of the current didn't exceed several tens of amperes. At high currents (up to 600 A), but small (less than 10 %) high-frequency pulsations (several kHz), the degree of destruction was several times lower. A similar picture is observed in the case of an unstable arc burning mode caused by shunting on the ledge. In this case, each attachment spot moves chaotically along the tungsten surface passing from heated parts of the surface to colder ones. This leads to a decrease in thermo-emission and an increase in the electron auto-emission and, consequently, to an increase in heat fluxes into the cathode.

It was found out that in hydrogen the heat losses into the cathode practically do not depend on the diameter of the tungsten rod, soldered flush into the copper casing, which varied in the experiments within the range of (3–10) mm.

Figure 4 shows the heat fluxes to the anode depending on the arc current for a plasmatron with d_2 = 8 mm, d_3 = 16 mm, l_2 = 50 mm, l = 100 mm at a hydrogen consumption of 1,1 g/s in the operating range of currents they reach (48–64) kW. According to the estimates, heat losses in the area before the ledge do not exceed 10 kW, therefore, the main heat losses occur in the zone behind the ledge. With an increase in I, heat losses increase rapidly. They are mainly determined by convective heat exchange between the heated hydrogen flux and the anode wall. That is why, the thermal efficiency of the plasmatron is mainly determined by the heat loss behind the ledge, and in order to reach its maximum value, the length l should be no more than it is necessary for the zone of arc shunting.

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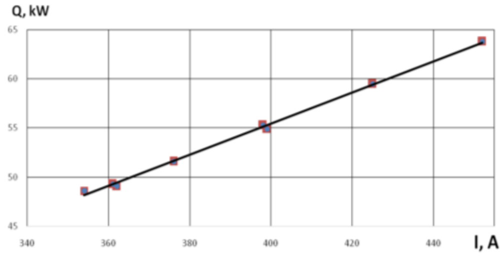


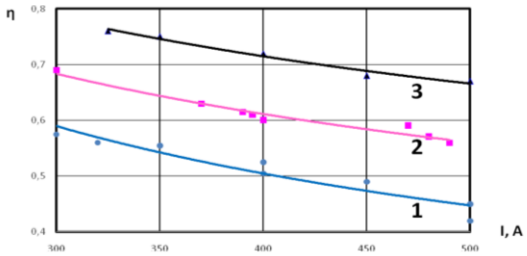
G_{H2} = 1 g/s, d_2 = 8 mm, d_3 = 16 mm,
l_2 = 50 mm, l = 100 mm

Figure 4 – Dependence of the heat flux into the anode on the arc current

The dependence of the thermal efficiency of the plasmatron on the value of the arc current at G_{H2} = 1 g/s, l_2 = 50 mm and different l values is shown in Figure 5. With an anode length close to the optimal (90 mm), the temperature of the jet at the plasmatron outlet reaches 3400 K, and thermal efficiency is (0,6–0,8). The dependence of the thermal efficiency on the current can be represented as:

$$\frac{1-\eta}{\eta} = 9,45\times10^{-5}\left(\frac{I}{G}\right)^{0,4}\bar{l}^{\,1,38}\left(pd\right)^{0,98}, \qquad (2)$$

WHERE $\bar{l} = \frac{l_2}{d_2} + \frac{l_3}{d_3}$, D_2 = 8 MM, D_3 = 16 MM.



1 – l = 150 mm, 2 – l = 116 mm, 3 – l = 90 mm

Figure 5 – Dependence of the plasmatron thermal efficiency on the magnitude of the arc current

Electrode erosion studies.

Experimental studies of the influence of the rod diameter on the specific erosion of electrodes in a wide range of currents at I = (370 ± 30) A have been carried out.

The dependence of the cathode specific erosion on the rod diameter is given in Figure 6. The lowest value of specific erosion is observed for the rod diametre d_c = 5 mm and is no more than (2–4)×10^{-9} g/(A·s). The amount of erosion was determined by weighing the cathodes before and after the experiment. Inspection of the cathode surface after long-term operation showed that the value of its specific erosion with rod diameters of less than 5 mm increases due to the fact that the arc spot begins to capture a part of the copper ring, which is being intensively destroyed. In some experiments at d_c = 5 mm, the spot on the tungsten surface did not always stabilize; in this case, the amount of erosion increased several times. The increase in erosion at d_c > 5 mm is associated with a deterioration in heat transfer and an increase in the temperature of the tungsten surface in the region of the near-cathode spot. At d_c = 10 mm, the arc spot moved over an area with a diameter of about 6 mm, forming in some place's craters of up to 2 mm with a diameter and depth after (6–10) hours of the plasmatron operation. Evaluation of the cathode service life based on the obtained specific erosion showed that at current values of about 400 A, the continuous cathode service life will be at least 200 hours.

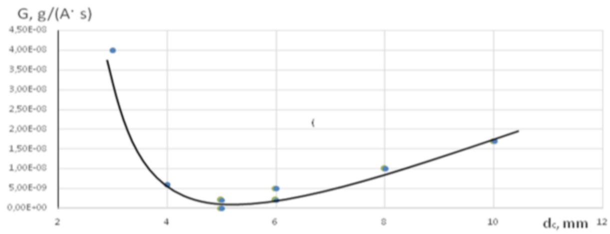


Figure 6 – Dependence of the cathode specific erosion on the tungsten rod diameter, at I = (370 ±30) A

Conclusion

Investigations of current-voltage characteristics, heat fluxes into the elements of the plasmatron, erosion of electrodes, thermal efficiency of the plasmatron for the generation of low-temperature hydrogen plasma have been carried out. On the basis of the developed technique, an original design of the plasmatron was developed. The obtained experimental results and engineering solutions can be used as initial data for designing industrial plasma installations of various capacity.

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