Investigation of the characteristics of an electric arc plasma torch with an output step electrode

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Abstract. The generalized formulas are obtained in the criteria form for calculating the energy parameters and the discharge chamber of the plasmatron. The calculation results and experimental data for the thermal efficiency and current-voltage characteristics of an electric arc plasma torch with an output step electrode are presented.

1. Introduction
For stationary heating of gaseous media to high temperatures \((3 \div 10) \cdot 10^3\) K, electric arc plasmatrons are widely used in scientific research and industrial technologies. They allow effectively implement chemical and metallurgical processes, create low-waste technologies and integrated processing of raw materials, obtain materials with specified physical and chemical properties, and significantly reduce the metal consumption of equipment.

Among the new applications of low-temperature plasma is the use of plasmatrons for the disposal and destruction of municipal, industrial and toxic waste. A further expansion of the scope of application of low-temperature plasma and an increase in the efficiency of using electric arc plasmatrons will be determined mainly by successes in the development of reliable and easy-to-maintain technological plasmatrons with a high electrode life [1].

The practice of using two-chamber electric arc plasmatrons with smooth copper cylindrical (tubular) electrodes has shown their high reliability when heating oxygen-containing media. In these plasmatrons, the internal electrode, as a rule, serves as the cathode, and the output electrode serves as the anode [2].

The working gas is fed into the plasma torch through swirl rings. The arc column is stabilized by vortex flow and is located on the axis of the electrodes. In the cathode cavity, the radial portion of the arc burns in the zone where two flows of the plasma-forming gas meet. In the output electrode, the anode section of the arc burns in the arc bypass zone. With increasing current, this zone shifts toward the internal electrode, the arc length decreases, and the voltage across the arc decreases. In this case, heat loss in the output electrode increases. The simultaneous voltage drop across the arc and the increase in heat loss, as practice shows, lead to the fact that when the current changes 3 times, the useful power of the plasma torch changes only 1.5 times, and the thermal efficiency, for example, at a current of 300 A does not exceed 65 - 70%.
2. Experimental installation

The design diagram of the plasma torch (Fig. 1) differs from the two-chamber one in that the output electrode is made stepwise expanding [3]. A step electrode is used in single-chamber plasmatrons to obtain an increasing current-voltage characteristic (CVC) of an arc [2]. In such an anode, behind the step, the flow is interrupted, and the hot gas adjoins the wall in a limited region of the wide part of the anode (indicated by a dotted line). The anode section of the arc is also adjacent to the electrode in this region (here, the zone of predominant arc shunting), which ensures fixation of the average length of the arc discharge when the current changes. As a result, the slope of the voltage drop across the arc decreases and a section appears with increasing CVC of the arc.

A similar phenomenon is observed in a two-chamber plasmatron with a step output electrode-anode (Fig. 1). In a two-chamber plasma torch, this phenomenon is much less pronounced. However, the average arc length is fixed and therefore the voltage on the arc changes significantly with the increasing current than in a two-chamber plasmatron with a tubular anode.

The location of the radial arc section in the inner electrode is determined by the ratio of the flow rates G1 and G2. Given pressure pulsations and gas flow rates, electrode erosion occurs in zone A (Fig. 1). The plasma torch electrodes are intensively cooled by water.

Experimental studies of the plasma torch were carried out at the stand of the Institute of Thermophysics SB RAS. The electrical circuit of the installation is shown in Figure 2.
The power source is two APR-404 rectifiers, with an open-circuit voltage $U_{xx} = 660$ V. Ballast resistance $R_b$ from 1 to 10 Ohms is applied in the form of a water pipe-in-pipe rheostat to control the arc discharge current. The rheostat is controlled by an analogue signal from 4 to 20mA of the process control system. For ensuring a visible break in the power circuit, a load switch is used. Management and control of the circuit breaker occur from the operator's workplace. The control signal is digital. An automatic system receives a signal to turn it on. The plasma torch is triggered by a high-voltage (~ 10 kV) high-frequency (~ 10 kHz) oscillator to which a digital signal is supplied for the breakdown of the interelectrode gap. Measurements of current and voltage of the arc discharge are established in the process control system. The values of the measured parameters are displayed on the operator's workstation. Measurement of water and plasma-forming air flow rates is carried out by electronic flow meters of the Sierra type connected to the common ACS network. From all these parameters, control signals are brought into the industrial controller. Management and measurement of all parameters are carried out through an industrial controller. The received measurements are saved in the database.

3. Research results
Figure 3 shows the $I - V$ characteristics of the arc in the studied range of airflow rates and the geometric dimensions of the electrodes.
Figure 3. Current-voltage characteristics of the arc. 1 – G₁ = G₂ = 4 × 10⁻³ kg/s; 2 – G₁ = G₂ = 5 × 10⁻³ kg/s; 3 – G₁ = G₂ = 6 × 10⁻³ kg/s.

It is seen that with a decrease in the discharge current, the voltage across the arc increases. At I ≥ 200A, the voltage is practically independent of the current strength and tends to increase. As the lines of equal powers show, the plasma torch stably works in the power range of 40 ÷ 100 kW.

The experimental data on the I − V characteristics of the arc are similarly with [2] summarized in the criteria form (all parameters in the SI system) [3]:

\[ U = 72 \left( \frac{I^2}{Gd_x} \right)^{-0.05} \left( \frac{G}{d_y} \right)^{0.25} \left( \frac{pd_z}{d_y} \right)^{0.35} \tag{1} \]

In the studied range of changes in parameters and complexes, the convergence of the calculated and experimental data does not exceed 7%.

3.1. Heat useful efficiency

The thermal efficiency of the plasma torch η_T is determined by the heat loss in the electrodes Q_n. All water-cooled structural elements of the plasma torch are connected to temperature sensors. The incoming signal from the sensors was fed to normalizing converters and then to the controller. The calculation of η_T was carried out according to the formula:

\[ Q_n = c_p \cdot G_x \cdot (T_g - T_x) \]

and

\[ \eta_T = 1 - \frac{Q_n}{P} \]

where \( c_p \) is the heat capacity of water, \( G_x \) is the water flow rate, \( P \) is the power of the plasma torch, \( T_g \) and \( T_x \) are the water temperatures at the inlet and outlet, respectively.

Figure 4 presents a comparison of the thermal efficiency of plasmatrons with a smooth output electrode (1) and with a step electrode (2).
Figure 4. The dependence of the thermal efficiency of the plasma torch on the current. 1 - plasmatron with a smooth electrode, 2 - plasmatron with a stepped electrode.

It can be seen that the efficiency of the plasma torch with a step electrode due to optimization of the length of the output electrode significantly exceeds the efficiency of the plasma torch with a tubular electrode.

The power of the plasma torch and the mass-average temperature of the plasma are controlled by a change in the current $I$, airflow $G$, electrode size and pressure $p$. The resource also depends on these parameters. The variation of the current, geometrical and flow parameters of the plasma torch shows that at the maximum current $I = I_n$ and the minimum gas flow, the mass-average plasma temperature at the exit of the plasma torch does not exceed 4600 K. With increasing flow rate $G$, the plasma temperature decreases. For example, at a current of 300 A, with an increase in gas flow from $8 \times 10^3$ kg / s to $12 \times 10^3$ kg / s, the average mass temperature of the plasma decreases from 4600 K to 3500 K.

The choice of current $I_n$ is quite arbitrary and is determined by the required power of the plasma torch, but $I_n$ should not exceed the critical current $I_c$, above which the internal electrode-cathode will quickly collapse.

4. Conclusion

The generalized formulas are obtained in the criteria form for calculating the energy parameters of the plasmatron, which are necessary for creating industrial samples of plasma generators of similar design schemes.

It is shown that a two-chamber plasmatron with a stepped output electrode due to fixation of the average arc length has a higher thermal efficiency than a plasmatron with smooth electrodes.

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