Laboratory and technological electric-arc plasma generators

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Abstract. The constructive schemes of electric-arc plasmatrons were analyzed by energy and erosion characteristics. The effect of arc shunting on plasmatron classification is presented. The effectiveness of barrier cooling in plasmatron channel with a sectioned interelectrode insert is determined. The criteria for the efficiency of tubular electrodes in plasmatrons with gas-vortex stabilization of an arc discharge are given. The role of vacuum plasmatrons in creation of plasma-vacuum electric furnaces is shown.

1. Introduction
The electric-arc generator of low-temperature plasma (hereinafter referred to as plasmatron) is an electrotechnical, thermal and gas dynamic apparatus for heating the gaseous substances to the temperatures from 3000 to 20,000 K. Its efficiency is determined by stability of arc discharge glow in a wide range of determining parameters: current and voltage of the power supply source; type, pressure and flow rate of the plasma-forming gas; high enthalpy of the heated gas; long life of electrodes, counted by many hundreds of hours.

Over the past decades, the methods for calculating plasmatrons of various design and plasma reactors for obtaining target products have been developed. Important results to increase the thermal efficiency of plasmatrons due to the gas curtain of discharge chamber walls have been obtained. Due to constructive solutions and theoretical analysis of near-electrode processes, the actual tasks of increasing the resistance of electrodes, when the resource of 1000 hours of continuous operation is not unattainable, were significantly advanced.

Finally, the similarity methods in development of technological plasmatrons played a very positive role, when it became possible to scale the plasmatrons for industrial installations based on the tests of laboratory models with the use of criterial dependencies.

2. Arc shunting and design features of plasmatrons
One of the fundamental electrophysical processes in the chamber of arc discharge glow, which determine electrical, pulsating and erosive characteristics of the plasmatron, is arc shunting: an electric breakdown between the discharge column and wall of a hollow cylindrical electrode. Shunting determines the arc length and average value of potential drop on it, extension of destruction zone of the inner electrode surface, pulsation parameters of the arc and plasma jet, and it is the cause of
formation of the falling volt-ampere arc characteristic. As a result of these processes, some average length of the arc is set, which is called the self-stabilizing length.

Despite the variety of constructive solutions for electric-arc plasmatrons for scientific research and technological applications, their classification is mainly based on the arc shunting process. The use of a sectioned interelectrode insert (IEI) and stepped outlet electrode excludes this process along the entire length of discharge chamber or creates favorable conditions for arc shunting behind a ledge. At that, the average length of the arc discharge becomes quasi-fixed, which leads to increasing volt-ampere characteristics of the arc and an increase in stability of arc glow in the power source-plasmatron system.

Figure 1 vividly confirms the above with respect to three most common classes of jet arc plasmatrons with gas-vortex stabilization of the arc [1, 2]. Firstly, these are plasmatrons with self-stabilizing arc length, determined by the shunting mechanism, and the volt-ampere characteristic of the arc (VAC) is of a descending nature (curve 1). Secondly, these are the plasmatrons with a fixed average arc length that is less than the self-stabilizing one because of using an outlet electrode of the stepped geometry. The VAC of the arc is U-shaped, i.e., the descending and ascending sections are clearly traced (curve 2). Finally, these are the plasmatrons with a fixed average arc length greater than the self-stabilizing one. For these plasmatrons, the VAC of the arc in the long channels is slightly descending (curve 3).

According to analysis of the $U-I$ characteristics of these three classes of plasmatrons (figure 1), the same arc discharge power $P$ can be achieved by applying one of the plasmatron schemes, taking into account $I_3 < I_1 < I_2$ and voltage level $U_i$ ($i = 1, 2, 3$). The choice of design of a plasmatron is determined by many factors (necessary power, disposable power source, continuous operation, etc.) for a particular process.

Figure 2. Scheme of plasmatrons with self-stabilizing (a) and fixed average arc length (b). a – with end thermocathode: 1 – thermocathode, 2 – outlet tubular electrode, 3 – swirl ring, 4 – arc, 5 – solenoid; b – with average length stabilization by a ledge: 1 – inner electrode, 2 – outlet electrode of stepped geometry, 3 – vortex chamber for gas introduction with flow rate $G$. 

Figure 1. The volt-ampere arc characteristics for three classes of linear plasmatrons.
Among the simplest designs, there are the single-chamber plasmatrons with an end thermocathode (figure 2) with the power of 10-100 kW for heating various gas media in scientific research and technological processes of plasma spraying, metal reducing from oxides, producing silicate melts, carbides, borides, and ferroalloys. The replacement of the end thermocathode by a cup-shaped or tubular electrode expands the series of plasmatrons to the two- and three-chamber schemes.

The powers of plasmatrons of these designs vary from 10 to 50 kW for the EDP-104 type as a common design of the laboratory pattern; 10-100 kW and 300-500 kW for the EDP-109/200 and EDP-107 type for the pilot plants, including production of plasma-chemical reactors and devices with the total power of 1500 kW. Such reactors have successfully proved themselves in the technological processes for production of pigment titanium dioxide and manganese ferroalloys.

The range of laboratory and experimental patterns of the arc plasmatrons with the power of up to 100 kW includes also the vapor-water, hydrogen, and two-jet setups. The latter allow us to act on the material being processed not only by a plasma jet, but also directly by an arc discharge.

An effective means of eliminating the process of reducing the arc length with increasing current during shunting is the use of an interelectrode insert (IEI) consisting of the isolated short metal cooled sections. To reduce heat losses, a part of the working gas is injected into the sectioned channel to the intersection gaps; this is the so-called barrier cooling. The results of investigation of multi-gap injection of cold gas in a long channel with IEI are described in detail in the monograph [3].

The plasmatron with IEI is a reliable and multi-purpose tool for the laboratory research, and it is very effective in technological processes. For the given gas flow rate, pressure and other determining parameters, an increase in enthalpy of the heated gas is possible not only by changing the arc current, but also by other free parameters such as the arc length and electric field strength.

The design of the EDP-119 plasmatron with a sectioned IEI with the power from 100 to 1500 kW is shown in figure 3 [4]. It is designed for heating various gases and gas mixtures with thermal efficiency of 0.8 - 0.9.

A prototype of 10-megawatt plasmatron with IEI GNP-10 was developed for hydrogen heating based on the experimental plasmatron EDP-119. When creating the plasmatron, a three-stage (modular) IEI system with inner diameters $d_1$, $d_2$, $d_3$, distributed gas supply and autonomous cooling of each stage was used. Experimental studies were carried out at truncated assemblies of all stages. Each module consisted of 20 sections with diameters $d_1 = 20$, $d_2 = 40$, $d_3 = 60$ mm. The maximal plasmatron power was 4 MW, thermal efficiency was $0.83 \div 0.75$, and bulk temperature of hydrogen heating was 3800 K.

3. Electrode erosion and plasmatron service life

Without diminishing the urgency of solving the problems of arc glow stability in the gas flow and optimizing the thermal losses to the discharge chamber elements, we should note that the problem of plasmatron service life remains the most important. The reliability requirements of plasma generators are mainly related to the resource of the most heat-stressed elements: electrodes.

The rate of electrode material destruction (erosion) is customarily characterized by specific erosion $\bar{\alpha}$, which is determined as the loss of electrode mass $\Delta m$, kg, referred to the current strength $I$, A.
per time unit \( t \), s, i.e., \( \bar{G} = \Delta m/(It) \), kg/C. Knowing the experimental values of \( \bar{G} \) and \( \Delta m \), it is easy to estimate the time of continuous operation of electrode at given arc current \( I \).

When heating inert gases and hydrogen in the single-chamber plasmatrons with an end electrode-cathode, a thermionic tungsten cathode is used, and hafnium (zirconium) thermochemical cathode is used for oxidizing media. Long operation of thermal cathodes is provided by the fundamental physical phenomenon: recirculation of electrode ions in the zone of a stationary cathode arc spot. Here we note that recycling is in the base of the cathode assembly with constant renewal of a thermionic insert from the gas phase material: pyrolytic carbon.

Experimental data on specific erosion of tungsten cathodes as a function of arc current in different gases are shown in figure 4 [2].

The measurement results scattering is largely due to the purity of gas media. The given values of \( \bar{G} \) are approximately two orders of magnitude smaller than those for commonly used rod tungsten. The results on specific erosion of tungsten cathode in the range \( \bar{G} = 10^{-12} – 10^{-13} \) kg/C (figure 4) were obtained at good stabilization of an arc spot, use of chemically pure gases, and optimization of the temperature regime of the working surface of cathode. At such values of \( \bar{G} \), the thermocathode resource of 300-500 hours is achieved at arc discharge currents of up to 600–700 A.

The thermochemical cathodes have proven themselves in plasmatrons for air-plasma cutting of metals and in laboratory patterns of experimental plasmatrons for heating air, water vapor and other oxygen-containing media.

In plasmatrons with gas-vortex stabilization of arc, the circumferential velocity component \( V_{\phi} \) rotates the near-electrode region with a reference spot to reduce \( \bar{G} \).

When studying erosion of copper tubular electrodes by current, we determined a characteristic feature in dependence of specific erosion on arc current: the critical current strength \( I_{cr} \), after which erosion increases sharply. In this regime of arc discharge glow, double arcing and arc spot delay are observed. One of the reasons for these phenomena is the loss of stability by the rotating gas flow, which stabilizes the arc.

It should be noted that the higher \( V_{\phi} \), the greater the stabilizing effect of a swirling gas flow. Since \( V_{\phi} \sim G/pd \) (\( G \) is gas flow rate, kg/s, \( p \) is pressure, Pa, \( d \) is electrode diameter, m), and values \( G, p, d \) are easily measured and monitored, then ratio \( G/pd \) can be considered as one of the criteria that determine the effect of arc discharge stabilization. Another criterion affecting the gas flow stability in electrodes is arc current \( I \), A.

The analysis of experimental and calculated data made it possible to determine the necessary conditions for the long service life of electrode-cathode in the air medium [2]:

\[
G/pd \geq 2 \cdot 10^{-6}; I < I_{cr} = 1.6 \cdot 10^{6} \sqrt{G/p}.
\] (1)

The similar relationships were derived for the anode:

\[
G/pd \geq 4 \cdot 10^{-6}; I < I_{cr} = 1.6 \cdot 10^{6} \sqrt{G/p}.
\] (2)
Relationships (1) and (2) can be called the performance criteria for the copper tubular electrodes. They allow us to estimate the resource of continuous operation of electrodes even at the stage of plasmatron design for calculated parameters \( G, d, p \).

4. Vacuum plasmatrons of laboratory and industrial type

Such plasmatrons are created using the hot hollow cathodes with plasma-forming gas supplied into their cavity. In the simplest plasmatron design, the cathode is a cylindrical tube (tantalum, tungsten) with inner diameter \( d_1 \) and outer diameter \( d_2 \), through which gas (argon, helium, nitrogen) is introduced into the low-pressure chamber. An open end of the tube is directed toward the anode, located at distance \( L = 10–500 \text{ mm} \) from the cathode. The diameter \( d_1 \) varies from 10 to 60 mm depending on the input power, and tube wall thickness \((d_2−d_1)/2\) is always taken to be at least 2 mm [5].

In optimal regimes of hollow cathode operation, specific erosion is \( 10^{-9} – 10^{-10} \text{ kg/C} \) at \( I/d_1 = (6 - 10) \times 10^4 \text{ A/m} \), which ensures a long electrode life during the process.

Vacuum plasmatrons are the basis of vacuum plasma electric furnaces as well as plasma-induction furnaces and electric furnaces with a cold crucible. In recent decades, new vacuum plasma industrial technologies for production of spheroidized and flake powders, remelting refractory metals, ion nitriding, and others have been developed.

The obtained fundamental results of research and development of vacuum plasmatrons and technologies on their basis made it possible to create the industrial vacuum plasma electric furnaces with single power of plasmatrons from 100 to 1000 kW and duration of continuous operation of plasmatrons not less than 500 h [5].

5. Conclusions

These results of research and development relate to the minor part in the total volume of laboratory and industrial plasmatrons and plasma technologies based thereon. The developed plasmatrons, plasma chemical reactors and electric plasma furnaces provide pilot industrial productions for processing/disposal of organochlorine and carbon-containing waste, ignition of pulverized coal flows in the boilers of thermal power plants, spraying the hardening and heat-resistant powder materials, recovery of metals from oxides, production of ferroalloys and ultrafine powders of carbides, nitrides and many other important technologies.

References

[1] Zhukov M F, Zasypkin I M, Timoshevskiy A N 1999 Electric-Arc Generators of Thermal Plasma (Novosibirsk: Nauka)
[2] Cherednichenko V S, Anshakov A S, Kuzmin M G 2011 Plasma Electrotechnological Installations (Novosibirsk: NSTU)
[3] Leontiev A I, Volchkov E P, Lebedev V P 1995 Thermal Protection of Plasmatron Walls (Novosibirsk: IT SB RAS)
[4] Zhukov M F 1980 Electric-Arc Plasmatrons (Novosibirsk: IT SB RAS)
[5] Cherednichenko V S, Yudin B I 2010 Vacuum Plasma Electric Furnaces (Novosibirsk: NSTU)