Generator of chemically active low-temperature plasma

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Abstract. A new generator of high enthalpy \( H_0 > 40 \text{ kJ/g} \), chemically active nitrogen and air plasmas was designed and constructed. Main feature of the generator is an expanding channel of an output electrode; the generator belongs to the class of DC plasma torches with thermionic cathode with an efficiency of 80%. The generator ensures the formation of a slightly divergent plasma jet \( (2\alpha = 12^\circ) \) with a diameter of \( D = 10–12 \text{ mm} \), an electric arc maximum power of 20–50 kW, plasma forming gas flow rate 1.0–2.0 g/s, and the average plasma temperature at an outlet of 8000–11000 K.

Generator of low-temperature plasma (GLP) has attracted the attention of specialists in the field of gas discharge physics and low-temperature plasma, and in the field of high-temperature gas dynamics by the fact that in the discharge gap of GLP the temperature range varies from thousands to tens of thousands degrees. This provides great opportunities for research in the thermal, electrical and optical properties of gases, as well as for the research in various plasma-chemical reactions [1–4].

To do these researches it is necessary to have a reliable GLP, in the discharge gap of which high-enthalpy plasma stream of chemically reactive gases (nitrogen, air) is created. As such plasma source a GLP with vortex stabilization and divergent channel of an output electrode was used, which provides high flow performance and long service life of the plasma torch as well as efficient heating of the working environment and small thermal losses in the water-cooled parts of the device [5, 6]. Typically, the GLP with a longitudinal gas flow are constructed with a cylindrical channel of constant cross section. The electrical discharge, features of a high-temperature gas flow, and parameters of the plasma generator with such channel are well known [7, 8]. The plasma torch with a constant cross-section channel has several flaws: falling current-voltage characteristic (CVC), unsustainable modes of operation, low thermal efficiency. That is why in order to achieve the desired average plasma temperature at the outlet a lot of input power is required, which in turn affects the lifespan, energy efficiency and stability of the plasma torch. In addition, stricter requirements for the supply of electric power are required to stabilize the arc. In such generators to stabilize the arc and its insulation from the walls of the channel porous injection, axial flow or twist of gas are used [4, 8], as well as various cavities, ledges, diaphragms, interelectrode segments are implemented [9], which complicate their design.

Equipping plasma torch with gas track with divergent channel of an output electrode enables the arc burning in a laminar stream at high velocity of gas at the inlet [5,6]. Another important
The advantage of this plasma torch is its current-voltage characteristic (CVC) with an expanded zone of stable arc burning [5,6]. The advantages of the plasma torch with an expanding channel allow it to provide an effective work at widely varying parameters. So, in order to obtain high enthalpy plasma stream of the chemically active gas for the study of plasma interaction with the thermal protecting coatings a plasma torch with combined nozzle-anode section and expanding (2α = 12°) discharge channel was constructed (figure 1), where the nozzle entry diameter is 4 mm, outlet diameter 10 mm, and the length of the gas path is 30 mm. This design helped increase efficiency to 80%, and achieve the output stream (H0 > 40 kJ/g) of chemically active nitrogen or air plasma with a characteristic diameter of 12 mm. At full power of the electric arc 20–50 kW, the flow rate of the plasma gas of 1.0–2.0 g/s, the plasma-average outlet temperature is 8000–1000 K, which is more than the outlet temperature of conventional GLP operating under similar conditions.

Figure 2 shows CVC of the constructed plasma generator with the working gases of nitrogen and air at two different values of gas flow rates. It is evident that the CVC has practically unchanged voltage with the increase of the arc current and an extended (as compared with the discharge in cylindrical channels) zone of steady arc burning.

Also in [10] the high metrological “quality” of electric arc DC plasma torches with an expanding output electrode channel is justified, associated with high reproducibility and stability of electric arc parameters and spatial-temporal radiate characteristics of strongly ionized plasma.

The plasma chemical composition and the flow parameters of high-enthalpy plasma were determined by spectroscopic methods [5,6] with the use of three-channeled spectrometer AvaSpec 2048 with a spectral resolution of 0.05–0.2 nm, which monitors radiation (with the frequency of 3–4 spectra/s) along the axis of the plasma stream in spectral range of 200–1100 nm. Figure 3 shows an example spectrum of air and nitrogen plasmas during the plasma treatment of isotropic graphite MPG-6. The presence of atomic spectra of N_I and O_I in its respective plasmas allow the use of “Boltzmann exponent” method to determine the electron temperature of plasma T_e [11]. The concentration of electrons in the axial region of the plasma jet can be estimated using the half-width of hydrogen atomic line H_alpha and H_beta. For example, at the nozzle outlet at a current of 250 A the electron temperature and concentration of nitrogen plasma is T_e = 10 kK, n_e = 5 × 10^{16} cm^{-3} and of air plasma is T_e = 8 kK, n_e = 10^{16} cm^{-3}.

As part of the verification of the plasma torch’s profiled nozzle’s acceleration characteristics, as well as the gas flow rate characteristics the experiments were carried out to measure total pressure with the use of Pitot tube. The pressure is measured by a current sensor Honeywell Eclipse OEM Pressure Transducer with a working range of P = 0–20.413 atm. with idle current of i_0 = 4 mA and a linear dependence of the pressure drop from the current dP/di = 1.2927 × 10^8 Pa/A. The current is measured by a digital microammeter with a precision of δi = 1 µA [12]. Measurements have shown that in nitrogen and air plasma, depending on the initial conditions; at a distance of 0–30 mm from the nozzle of the plasma torch the near axis speed changes in the range of 1000–300 m/s.

With the help of calorimeter (water-cooled end of a copper cylinder with the diameter of d_0 = 20 mm with a “guarding” disk) in a “settled” heat-transfer mode “plasma stream–calorimeter” calibration measurements of thermal power W_Q = C_p Q H_2O (t_out − t_in) transferred from plasma stream to the surface were performed S_cal = π(d_0^2)/4, with varying values of arc power, gas flow rate and the distance from the nozzle h. Studies have shown that the optimal mode of operation, ensuring efficient operation and prolonged lifespan of the plasma torch with the expanding channel is the current range of 200–400 A for nitrogen, and 150–200 A for air at the working gas flow rate of—1.5 g/s. The change in the plasma torch power from 20 kW to 50 kW and the distance h from 30 to 10 mm provides a plasma jet heat flux of 0.1 to 10 kW/cm^2, the temperature and the concentration of electrons at the maximum point is T_e = 10 kK, n_e = 10^{16} cm^{-3}. 


Figure 1. The design of a 50 kW plasma torch 1—nozzle; 2—the case of the plasma torch; 3—anode section; 4—insulator; 5—cathode; 6—section of refractory metal; 7—cathode holder; 8—cathode cooling tube.

Figure 2. The current-voltage characteristic of the discharge in nitrogen (a) and air (b).

Constructed generator of high enthalpy chemically active nitrogen and air plasma jets with an expanding output electrode channel has a higher efficiency when compared to traditional
electric arc plasma torches. In addition, with an equal power input the GLP resource is mainly determined by the force of the discharge current. Then in an expanding channel the internal surface area is greater and so the current density is lower than in a cylindrical channel, thus the resource of the device is increased. With the discharge channel diameter of about 10–12 mm the plasma torch generates plasma at the outlet with the following parameters: average weight temperature of $\sim 11000$ K, the electron density in the axial plasma region of $\sim 2 \times 10^{16}$ cm$^{-3}$.

This GLP can be used to investigate the destruction of heat-shielding materials exposed to chemically active plasma and the implementation of various plasma-chemical reactions and by processing of plasma flows spectroscopic information provides unique in scope and accuracy data on the radiative characteristics of atomic and ionic spectrums. The experimental data and engineering solutions can serve as the starting point for the design of the GLP with a power of up to 1 MW and above.

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