Production and study of megawatt air–nitrogen plasmatron with divergent channel of an output electrode

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Abstract. Megawatt generator of high-enthalpy air plasma jet ($H \geq 30$ kJ/g) is constructed. Plasmatron belongs to the class of plasma torches with thermionic cathode, tangential swirl flow and divergent channel of an output electrode–anode. Plasma torch ensures the formation of the slightly divergent ($2\alpha = 12^\circ$) air plasma jet with the diameter $D = 50$ mm. The current–voltage characteristics of the plasma torch has virtually unchanged voltage relative to its current with enhanced (compared with arcs in cylindrical channels) stable combustion zone. Preliminary analysis of the obtained air plasma spectra shows that at a current of 1500 A near-axis zone of the plasma jet is characterized by a temperature of up to 15000 K, and the peripheral radiating area has a temperature of 8000–9000 K.

Low-temperature plasma generator (LTPG) has attracted the attention of specialists in the field of gas discharge physics, low-temperature plasma and high-temperature gas dynamics with the fact that in the discharge gap of LTPG temperature range varies from thousands to tens of thousands of degrees, which is of great interest for research in thermal and electro-optical properties of gases, as well as for various plasma-chemical reactions. The ability to obtain homogeneous and heterogeneous gas flows with predetermined pressures and temperatures over a wide range of speeds (up to supersonic) make LTPG unique tool for modeling of high temperature flow interaction with any surface material.

In recent years, great interest in science and technology is caused by megawatt plasma torches, which produce a high-enthalpy air plasma jets with large diameters for use in plasma-chemical technologies. The interest is because they can be used to obtain extremely high temperatures, which are inaccessible by chemical methods, they are reliable, and they have a simple automatic control of power and modes of the plasma torch.

LTPG with an expanding channel of an output electrode (figure 1) [1,2] can be used as such plasma torch. Opting for the plasma torch of this type is associated with the fact that this construction enables the arc burning in a laminar flow at high gas velocity at the nozzle inlet.

Air plasma torch with the power of 1 MW is a generator of low-temperature plasma with the special design of the elements: cathode, anode and the nozzles, which resulted in a relatively high performance when working on the air. To protect the cathode against erosion during operation in a chemically active medium of air nitrogen is supplied into the gap between the cathode 2 and the first nozzle 3 with the flow rate of 2 g/s, thus nitrogen plasma is generated in the cathode.
Figure 1. The design of the experimental stand based on an air–nitrogen 1 MW plasma torch: 1—cathode holder; 2—cathode; 3—first nozzle; 4—first nozzle holder; 5—air box; 6—second nozzle holder; 7—second nozzle; 8—third nozzle holder; 9—third nozzle; 10—anode holder; 11—anode insertion; 12—spectroscopic section with windows; 13—probe; 14—stand for the probe; 15—a tube and coolant tank.

Lower along the channel air is supplied axially through the air box 5 at a rate of up to 16 g/s, which is mixed with nitrogen plasma and purged into the anode section through the nozzles 7 and 9 that ensures the formation of a slightly divergent ($2\alpha = 12^\circ$) plasma jet with the diameter $D = 50$ mm at the outlet of plasma torch, which then enters the coolant tube. The cooling system is designed in such a way so that water from the nozzle holder 3 is supplied to the nozzle holder 7 and then further into a cooler 15; water from the other elements of the plasma torch (cathode holder 1, nozzle holder 7 and an anode holder 10) is fed into the cooler 15. The total water consumption with a switched on pump is $\approx 1900$ g/s. After the cooler water goes to the water tank, after which it is pumped to the drainage.

To investigate the parameters of the plasma experimental stand is equipped with spectroscopic section 12 that has 7 windows, which allow for registration of the spectra with a resolution of the cross section of the plasma flow, as well as electric tungsten probe 13, which is fired into the plasma flow at a given depth and resides at that point for a given time.
Figure 2. The electron temperature obtained using 7 viewing windows (along the diameter of the jet) at two different currents and two gas flow rates.

Table 1. Operational parameters during start-up and continuous work mode of plasma torch.

| $I_{\text{start}}$, A | $I_{\text{cont}}$, A | $U$, V | $P$, kW | Air flow rate (start), g/s | Air flow rate (cont.), g/s | N flow rate, g/s |
|----------------------|----------------------|-------|---------|---------------------------|---------------------------|--------------|
| 900                  | 1500                 | 285   | 428     | 6                         | 16                        | 2            |

Preliminary analysis of the obtained air plasma spectra shows that, at a current of 1500 A, near-axis zone of the plasma jet is characterized by a temperature of up to 15000 K, and its peripheral radiating area has a temperature of 8000–9000 K (figure 2). The electron temperature is determined by the relative intensities of the spectral lines NI and OI with different excitation energies of radiating levels [3]. Relative intensities of multiple lines of CuI (wall material of the plasma torch) within the wavelengths of 400–525 nm can serve as methods to assess the plasma jet in its peripheral regions, these spectral lines cover a wide range of excitation energies 3.82–8.00 eV. The electron density of the air plasma is measured by the Stark component of the Voigt contour of a spectral line $H_{\alpha}$ (linear Stark effect) and atomic line OI 725.4 nm (quadratic Stark effect). In the axial region of the in the megawatt plasma torch plasma the electron density amounts to $(3 \pm 1) \times 10^{16}$ cm$^{-3}$.

One of the most important characteristics of the discharge in the low-temperature plasma generator is its current–voltage characteristics (CVC); the features of the electrical circuit determine the nature of the CVC.

Falling CVC for LTPG with longitudinal gas flow and self-adjusting arc length, firstly entails
strict requirements for the electric power supply for stabilization of the arc. Secondly, as the current increases the arc voltage decreases, respectively, the arc power is increased slower than the current, while the resource in the LTPG is largely determined by the magnitude of the arc current.

Table 1 presents the parameters of the working plasma torch, where $U$—voltage between the cathode and anode of the plasma torch, $P$—power of the plasma torch, $I_{\text{start}}$ and air flow rate (start) are the current and air flow rate at the moment, when the plasma torch is switched on, $I_{\text{cont}}$ and air flow rate (cont.) are the current and flow rate at the moment, when plasma torch reaches stable working condition, $N$ (nitrogen) flow rate was kept the same through all the stages of the experiment. Figure 3 shows the working mode of the plasma generator for the working values shown in table 1. It shows that current and voltage does not change during the operation time of the plasma generator, which in turn shows the stability of the plasma torches operational environment.

To evaluate the efficiency of the plasma torch thermal characteristics of the installation were studied by determining the heat flow in its main units. Determination of heat flow was carried
out by measuring the flow rate and temperature $T_{\text{exit}}$ (at exit point) of water independently on the inputs and outputs of the installations cooled parts, which are listed in Table 2. The total efficiency of the plasma generator is $(428 - 86.9)/428 = 0.80$. All the measurements were made by computerized registration system, and the measurement results were processed automatically by specially developed software.

Acquired experimental data and engineering solutions are the basis for the design and construction of an industrial installation.

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