The investigation of an electric arc in the long cylindrical channel of the powerful high-voltage AC plasma torch

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Abstract. The comparison of conductivity obtained in experiments with calculated values is made in this paper. Powerful stationary plasma torches with prolonged period of continuous work are popular for modern plasmachemical applications. The maximum electrode lifetime with the minimum erosion can be reached while working on rather low currents. Meanwhile it is required to provide voltage arc drop for the high power achievement. Electric field strength in the arc column of the high-voltage plasma torch, using air as a plasma-forming gas, does not exceed 15 V/cm. It is possible to obtain the high voltage drop in the long arc stabilized in the channel by the intensive gas flow under given conditions. Models of high voltage plasma torches with rod electrodes with power up to 50 kW have been developed and investigated. The plasma torch arcs are burning in cylindrical channels. Present investigations are directed at studying the possibility of developing long arc plasma torches with higher power. The advantage of AC power supplies usage is the possibility of the loss minimization due to the reactive power compensation. The theoretical maximum of voltage arc drop for power supplies with inductive current limitations is about 50 % of the no-load voltage for a single-phase circuit and about 30 % for the three-phase circuit. Burning of intensively blown arcs in the long cylindrical channel using the AC power supply with 10 kV no-load voltage is experimentally investigated in the work. Voltage drops close to the maximum possible had been reached in the examined arcs in single-phase and three-phase modes. Operating parameters for single-phase mode were: current - 30 A, voltage drop - 5 kV, air flow rate 35 g/s; for three-phase mode: current (40-85) A, voltage drop (2.5-3.2) kV, air flow rate (60-100) g/s. Arc length in the installations exceeded 2 m.

1. Introduction

Global population and economic growth is accompanied by growth of energy consumption and waste cumulative weight. Therefore, there is an urgent need to develop new waste treatment technologies for electricity generation.

Promising methods for the solution of this challenge are plasma gasification and conversion [1-4] used for syngas production from organic, woodworking industry and agricultural wastes. Construction of powerful electric arc plasma torches with low operational costs is required for the development of mentioned above technologies. Usage of a multiphase (three-phase) AC system comprising AC arcs used as a basis of an electric arc plasma torch enables creation of a simple, low-cost and reliable
power supply system. Air usage as a plasma forming gas dramatically decreases operational costs of the electric arc plasma system.

IEE RAS (Institute for Electrophysics and Electric Power Russian Academy of Sciences) has an extensive experience in development of powerful multiphase electric arc AC plasma torches. Powerful single-chamber electric arc plasma torches with rail electrodes and power up to 500 kW have been created (figure 1) [5, 6].

![Figure 1. Single-chamber electric arc plasma torches with rail electrodes. Power 100 – 500 kW, supply voltage 480 V, arc current 500 – 1500 A, air flow rate 15 – 70 g/s.](image1)

The power increase of such plasma torches is attained by increase of arc current at sufficiently low voltage drop (about 200 V). However, the lifetime of electrode units of these plasma torches is 100 hours that is not enough for some plasmachemical applications. Power of the plasma torch can be increased without its resource indexes degradation by increasing of the arc voltage drop instead of the arc current. AC plasma torches with arcs burning in long cylindrical channels have been developed in IEE RAS (figure 2) [7-12].

![Figure 2. High-voltage electric arc AC plasma torch with rod electrodes. Supply voltage 6 – 10 kV, arc voltage drop 900-1200 V, arc current up to 35 A, plasma forming gas: air, argon, carbon dioxide, gas flow rate from 1 to 30 g/s.](image2)
In electric arc plasma torches of such type the power variation is controlled not by current change but by arc voltage drop change, which in turn depends on the change of plasma forming gas flow rate (see figure 3).

![Figure 3. Dependence of variation of arc voltage drop versus plasma forming gas flow rate for various values of power supply source current. Plasma gas is air.](image)

Thus, it is necessary to search for achievement of theoretically possible values of voltage drop for the used power supply. The possible arc voltage drop is 53 % from the idle-running power supply for a single-phase AC arc, and for a three-phase electric arc system the theoretically possible voltage drop is 33 - 35 %. What at the idle-running power supply of 10000 V can exceed 3000 V. At operation of the plasma torch on air at atmospheric pressure the strength in the arc lays in the range 10 - 15 V/cm, and the arc length, voltage drop in which is about 3000 V, should exceed 200 cm.

At present IEE RAS has achieved stable operation of the experimental three-phase AC plasma torch with arcs burning in long cylindrical channels. Figure 4 shows arc voltage drop versus flow rate of the plasma forming gas.

![Figure 4. Dependence of voltage drop from gas flow rate. Plasma gas is air.](image)
Thus the length of an arc remains constant and accordingly cannot influence the change of the electrostatic strength. The electric field strength is connected with the current density and conductivity by equation (1).

\[
\sigma = \frac{j}{E} = \frac{e^2 n_e}{2 \sqrt{3 m_e k T} \left( \sum_i n_{i} s_i + n_{ion} s_{ion} \right)}
\]  

where, \(\sigma\) – conductivity, \(j\) – current density (A/m\(^2\)), \(E\) – electrostatic strength (V/m), \(n_e\) – electron concentration (1/m\(^3\)), \(e\) and \(m_e\) – electron charge and mass (C) and (kg) respectively, \(k\) – Boltzmann (J/K), \(n_i\) and \(s_i\) – concentration and cross-section of neutral plasma components scattering (1/m\(^3\)) and (m\(^2\)) respectively, \(s_{ion}\) – cross-section of Coulomb scattering (m\(^2\)), \(n_{ion}\) – ion concentration (1/m\(^3\)).

2. Results of numerical simulation

Model is considered one of two channels of high-voltage AC plasma torch (one of three channels for three-phase plasma torch). Topology of the plasma torch is such that the separated channels have the same direction at a slight angle to each other. Each channel includes a hollow cylindrical electrode, loops of the tangential feeding of the plasma forming gas and the outlet nozzle. The gas flow is the same in all channels.

As the arc length remains approximately constant it is possible to draw a conclusion that with change of flow rate ratios of the arc conductivity or current density varies. Hence, the arc voltage drop changes owing to the change of thermo- and gas dynamic processes (regimes) of gas flow in the channel. It is required to investigate the change of gas flow in the channel depending on magnitude of a total gas flow rate. A cold blasting can be considered for this purpose as a first approximation and computing experiments are carried out. The investigation of gas flow in the channel was solved in three-dimension stationary problem statement. The approach developed for high-speed viscous compressible flows was chosen. Besides Navier-Stokes and continuity equations, the system is supplemented with the equation of energy and a set of the empirical constants accompanying connection of a turbulence model (\(k-\varepsilon\)). The fields of thermo and gasdynamic parameters distribution have been derived during computing experiments.

The grid containing \(2 \times 10^6\) meshes has been built in the independent grid generator for the solution of this problem. It has been thickened in the injection area for the correct solution.

It is necessary to carry out preliminary theoretical calculation of gas-dynamic parameters to setup parameters at the input rated operating conditions. Figure 5 shows the set of cross-sections transverse to the channel axis where visualization of flow was performed.

Figure 5. Layout of cross-sections.

The computing experiment has confirmed presence of a wall ring zone with the decreased to speed values (~10 m/s), which size and position depends on magnitude of gas flow rate and its distributions between supply loops. Figure 6(a) shows the field of module of the rotational component of the velocity vector for the total flow rate of supplied gas 68 g/s. The lines of gas flow are twirled on a
spiral in the vicinity of the axis of symmetry, values of modules of a speed vector and its rotational components are close to zero. Figure 7 shows that with increase in the total magnitude of the flow rate of the supplied gas this area of the decreased values is constricted to the channel axis of symmetry. Thus the wall current speeds in the vicinity of the cross-sections noted by numbers 6-11 in figure 5, increase. The process is accompanied by rise of disturbances transferred by a current upwards the stream from the third injection orifice (figure 6(h)) and significant change of the flow pattern in the nozzle area.

Figure 6. Field of module of the rotational component of the velocity vector for air flow rate 68 g/s.
In the cross-section area noted by number seven (figure 5) the flow acceleration up to speeds varying on the module over the range ~200÷350 m/s depending on magnitude of gas flow rate is observed.

![Comparison of field of module of the rotational component of the velocity vector for air flow rates](image)

Figure 7. Comparison of field of module of the rotational component of the velocity vector for air flow rates (a) 68 g/s, (b) 86 g/s, (c) 107.5 g/s.

3. Conclusion

The third injection orifice has the greatest influence on change of the stream speed. The sonic flow caused by the channel geometry is realized in its area, at high values of the total flow rate of the supplied gas. In this area there is an essential reduction of temperature and pressure due to flow acceleration. Analogue of such flow is a classical gasdynamic flow in the confuser. The greatest gradients of gas- and thermodynamic parameters are observed in the channel cross-sections in the areas immediately adjacent to the injection orifices.

The increase of wall velocity at growth of a total gas flow rate complicates the electric arc closing on the case, and also promotes its stabilization along the symmetry axis.

The calculations show that at high flow rates the flow is more compressed and arc-gas heat exchange is more intensive. As a consequence, it first of all can influence upon increase in current density.

The obtained results represent the first stage of creation of a virtual model of the electric arc interaction with a gas stream. In what follows it is planned to enter "energy supply" into this model. At present the mathematical model of an arc and its interaction with a stream is under development.

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