The investigation of movement dynamics of an AC electric arc attachment along the working surface of a hollow cylindrical electrode under the action of gas-dynamic and electromagnetic forces

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Abstract. Stationary electric arc alternating current plasma torches are used today for realization of plasma chemical technologies requiring relatively high energy input. Waste treatment is one these directions. The paper reports on experiment results directed towards the increase in the lifetime characteristics of electrode units of the powerful high-voltage electric-arc AC plasma torches. The solution to the problem of obtainment the uniform wear of a copper hollow cylindrical electrode achieved by the controlled movement of the arc attachment along the working surface was offered. Organization of gas supply in the near electrode area and application of alternating magnetic field ensured movement of arc attachment along the surface with average speed from 2 to 14 m/s. Arc current was about 47 A and 84 A, gas flow rate in near electrode area was about 5 and 4.5 g/s. Due to researches on the experimental prototype of a hollow cylindrical electrode, the erosion of its material reached only 3 µg/C, that enables production of the electrode assembly with life time above 1000 hours at currents in the arc up to 100-200 A.

Introduction
Currently, plasmachemical technologies are actively developed for efficient use of energy resources and implementation of ecologically safe methods for destruction and treatment of various wastes, including for the combustible syngas production [1-5]. The generator of thermal plasma is a key element of the majority of plasma chemical installations. Nowadays plasma torches are also actively used in power engineering for ignition and lightning of coal boilers [6]. The devices intended for operation in large-scale industrial installations should be powerful, efficiently transfer energy to the working gas, operate continuously for a long period of time and generally can operate in oxidizing media. Stationary electric arc plasma torches are very promising for these purposes. Westinghouse [7] and Europlasma [8] DC plasma torches are well-developed for industrial applications. The particular attention for a number of applications deserves the models using water or steam as a plasma forming gas [5, 9, 10]. A number of promising models of stationary AC plasma torches operating on various gases has been developed in IEE RAS. Among them are plasma torches using oxidizing media...
(including air): powerful single-chamber three-phase plasma torches with rod electrodes [11], single-phase and three-phase high-voltage plasma torches with power from 5 up to 100 kW with rod electrodes mounted in a separate cylindrical channels [12, 13] and single-chamber three-phase plasma torches with rail-type electrodes, with operating power up to 500 kW [14], and plasma torches working on a mixture of steam and air or another gas with power up to 100 kW were developed [15]. At present high-voltage AC plasma torches with hollow cylindrical electrodes are under development. Such plasma torches have the high arc voltage drop that enables essential current decreasing versus low-voltage models of the same power level and accordingly increase of the electrode lifetime. As a result these devices can provide continuous operation with high power and lifetime of electrodes more than 1000 hours. Prototypes of commercial plasma torches with power 200 and 400 kW are created. The devices with power of an order 1 MW are under development. This paper is devoted to investigation of movement dynamics of an AC electric arc attachment along the working surface of a hollow cylindrical electrode of such plasma torches. The purpose of this paper is presentation of results of the experimental researches obtained during development of new AC plasma torches.

**Experimental setup**

The investigations were carried out at the test bench of AC plasma torches equipped with required supply systems. The test bench comprises: power supply system, double-loop cooling system, system of preparation and supply of plasma forming gas and system of treatment and discharge of exhaust gases. Prototypes of AC plasma torches with cylindrical (hollow) electrodes developed by IEE RAS were used. Figure 1 shows the schematic diagram of the installation. The high-voltage three-phase plasma torch is connected to the AC power supply source of industrial frequency (50 Hz). While the plasma torch operates the arcs burn between three electrodes and have the general point behind the nozzle exit section.

![Figure 1. Schematic diagram of the experimental installation. 1 - Power supply, 2 - high-voltage three-phase plasma torch with cylindrical (hollow) electrodes, 3 - arc column, 4 - hollow cylindrical electrode, 5 - solenoid, 6 - pipe hole for photo and video shooting, 7 - terminal for connection of the power supply, 8 and 9 - upstream and downstream loops of tangential supply of plasma forming gas, 10 - high-speed video camera, 11 - recording industrial computer.](image)

In the bottom of Figure 1 (zoomed in) is shown the schematic diagram of one of three plasma torch channels (one of three phases) with electrode, solenoid, and peep hole. From both sides of a hollow electrode (upstream and downstream) are designed loops of tangential plasma forming gas supply. Rotation of the arc attachment in each of the electrodes is provided due to the tangential gas supply and the magnetic field of the solenoid installed coaxially around the electrode. The current and voltage analogue sensing transducers are incorporated for measurement of arc currents and voltages in the power supply. The industrial computer with an acquisition boards (with bandwidth of 10 kHz per
channel) is incorporated in the measuring system for data recording. Power of the plasma torch and effective values of electric parameters are calculated on their instantaneous values. There are automated pressure regulators - the flow meters which are also connected to the industrial computer for supply of the required plasma forming gas flow rate into the plasma torch gas inlet loops. The peep holes are provided for measurement of speed of the arc attachments on the electrode surface by means of a high-speed video shooting. Three monochrome high-speed video cameras which are a part of the measuring system, allow simultaneous synchronous recording of arc attachment movement along the three electrodes with speed of shooting 4000 fps.

**Description of experiments and main results**

Experiments were carried out on prototypes of the plasma torch working models. Considering the practical importance of the carried-out investigations, the principal criterion for the flow rate range selection for a gas supply mode variation and solenoid parameters for the magnetic field change were expediency and feasibility of providing these parameters during the plasma torch work in the industrial plants. Investigations were carried out on modes of the stable arc burning in the plasma torch electrode channels for the arc currents about 40A and 80A. Longitudinal and rotary moving of the arc attachment – in the axial and tangential directions was required for providing the long-lasting lifetime of electrodes. Figure 2 shows the photo of the arc attachment. The photo made through the peep hole under some angle to the axis of the plasma torch channel in order to see the electrode working surface.

![Photo of an AC electric arc attachment on the working surface of the cylindrical electrode. shutter speed 1/4000 s.](image)

The internal part of the cylindrical electrode surface, where during the plasma torch work the arc attachment leaves the trace, we will call a working surface. The arc attachment position on the electrode working surface in the longitudinal direction was possible to set by regulation of the flow rates in near-electrode loops of the plasma forming gas supply. The rotation speed of the arc attachment depends both on the gas supply mode, and on characteristics of the impressed magnetic field.

The AC arc attachment rotates under the action of the gas-dynamic forces, sliding over the electrode working surface during the plasma torch work. Plasma of the arc column does not have
enough time to relax at the current zero crossing, and the arc is ignited in the same channel in the each following half-period. The solenoid, which is forming a longitudinal magnetic field in the hollow electrode volume, is coaxially put on the electrode for the intensification of the arc attachment rotation. The solenoid coil is powered from the AC power supply, so that at the arc current polarity changing, the current direction in the coil changes. Thus, despite of the arc current polarity changing, the force direction, acting on the arc attachment, and promoting the intensification of its rotational movement remains the same. The magnitude of force acting on the charged particles of the arc column in the arc attachment area changes due to the sinusoidal change of the current in the coil. This force reaches the maximum value at the peak arc current and decreases at the moment of the current transition through zero. The connection of the AC coil in the opposite direction can cause the braking or even arc attachment moving towards to the gas flow, which is undesirable, as it leads to increase of the electrode material erosion and the reduction of its lifetime.

The magnetic field produced by a solenoid in the electrode channel was obtained using computer simulation. Figure 4 shows the schematic diagram of the electrode with the solenoid (a) and characteristic graphs of distribution of value of magnetic inductance on a working surface of an electrode in the longitudinal direction (b) and its distributions along the diameter of the electrode chamber (c). Values of magnetic inductance during the moments of time matching to maxima of currents in the solenoid windings, for the points of space laying on lines L and D are built in the graphs. Line L represents the generating line of the working surface, and line D coincides with the diameter.

Figure 3. Schematic diagram of the hollow cylindrical electrode with solenoid (a) and characteristic graphs of distribution of the value of magnetic inductance in the electrode channel at the moment of current maximum in the solenoid windings. Lines D and L – lines, along which are calculated the values of magnetic inductance, presented in graphs: (b) - longitudinal distribution of the magnetic inductance along the electrode working surface; (c) - distribution of the magnetic inductance on the diameter of the electrode chamber. Point A belongs to ring area with the maximum magnetic field density on the electrode working surface. Curve 1 shows magnetic inductance for plasma torch working with arc current of 47 A, curves 2-5 correspond the plasma torch working modes with arc current of 85 A.

Analysis of materials of a high-speed video shooting of the arc attachment movement along the electrode surface shows dependences of the arc attachment versus plasma torch operating parameters and characteristics of applied magnetic field. Shooting was carried out through the peep holes located in a back part of the electrode channel, with use of High Speed Video Cameras “Citius Imaging C100 Centurio” with a speed 4000 fps and exposure 2 µs. Speed of the arc attachment movement round a circle is non-uniform, it increases under the influence of electromagnetic forces at current maximum.
of a coil and decreases with its transition through zero. Mean values of tangential speed of the arc attachment were calculated on 50 complete revolutions for different regimes, showed in figure 3. For the arc current about 47 A without applied magnetic field the attachment velocity is about 2.5 m/s and it is rising twice when applied magnetic field density achieves $10^{-2}$T. For the arc current about 85 A without applied magnetic field the attachment velocity is about 3.2 m/s and it is rising from 4 to 14 m/s when applied magnetic field density accordingly changes from $7 \times 10^{-3}$T to $20 \times 10^{-3}$T.

Numerical calculations of gas-dynamic parameters in the near electrode area for comparison the arc attachment rotation speed and the gas flow speed for the examined modes of the plasma forming gas feeding were carried out. Considering the fact, that the main flow in the back part of the channel is formed by the cold gas, submitted tangentially, and that the part of the arc column, situated there, occupies rather small share of the channel volume, so that parameters of a cold gas flow rate (without arc presence) were calculated in a first approximation. The task was solved in the stationary statement for the viscous compressed air. The approach, developed for high-speed compressible flows, was chosen. Besides the Navier-Stokes equations and the continuity equations, the system was supplemented by the energy equation and a set of the empirical constants, accompanying the connection of the turbulence model ($k$-$\varepsilon$), at calculations. The Figure 5 shows the calculation data.

Figure 5. Plasma forming gas magnitude speed fields (m/s) in the electrode channel of the plasma torch in dependence of a total flow rate in near electrode loops of the plasma forming gas (air): (a) - 5 g/s, (b) - 9.4 g/s, (c) - 12.2 g/s; in the upstream and the downstream feeding circuits of the plasma forming gas (air). (d)-(f) - Representation of velocity fields for different distribution of flow rates between upstream and downstream gas feeding circuits. Arrows show the arc attachment areas: (d) - arc attachment is situated in back end of electrode, (e) - in the middle area and (f) - in the downstream end. Total gas flow rate - 4.5 g/s.

Figure 5 shows calculated gas velocity fields for plasma torch operation modes with different air flow rates supplied to the near electrode area. On each diagram can be seen location of slower near-wall flow, bounded on both sides (upstream and downstream) of a faster flow. Such areas are marked by arrows in diagrams (d)-(f). The electric arc attachment of working plasma torch stabilized in these locations, where the tangential velocity component makes the main contribution to the velocity magnitude (>99%). Diagrams (a)-(c) show velocity fields calculated for plasma torch operation modes with different air flow rates supplied to the near electrode area. Flow rates were from 5 to 12.2 g/s. Average speeds of the arc attachment moving under the influence of a magnetic field with an
inductance of about $10^{-2}$ T were experimentally obtained for the same flow rate modes. The arc current was 47 A. The average speed of the arc attachment under these conditions is approximately 3 times less than the gas velocity in the near-wall electrode channel area.

Figure 5 (d)-(f) shows gas magnitude velocity fields for three modes of gas feeding with different ratios of its flow rates through upstream and downstream near electrode loops. The arc rotates in regions bounded on both sides of a faster flow marked by arrows. In these regions the tangential velocity is more than 98% of the velocity magnitude. The arrows in the diagrams (d), (e) and (f) comply with the trace of the arc at the beginning middle and end of the working electrode surface (in the longitudinal direction). Thus, the position of the arc attachment can be adjusted on the working electrode surface in the longitudinal direction. This allows organizing a permanent rotational and reciprocating movement of the arc in the long cylindrical electrode over its entire surface by changing the ratio of flow rates in upstream and downstream near-electrode feeding loops. For represented on these diagrams modes were experimentally determined speed of the arc attachment moving under the influence of a magnetic field with an inductance of about $14 \times 10^{-3}$ T. The average speed of the arc attachment with a current about 84A slightly lags behind the velocity of the gas flow in the near electrode area and is about 80-90% of it. In reviewing should take into account that the values of the arc attachment speed are obtained experimentally, and the calculated values of flow rates are approximate and were obtained for the cold flow (excluding the arc in the working volume of the electrode) and that the real value of the flow velocity in the examined area may be different from calculated.

The speed of the arc attachment longitudinal motion depends on the rate of change of the flow rate proportion. Based on the results of a number of experiments it was offered for our device to organize continuous reciprocating motion of the arc attachment in the longitudinal direction (scanning) with longitudinal speed about 1 cm/s, it is successfully realized by gas supplying system, equipped with industrial automatic pressure controllers. Long-term 300-hour experiments showed that longitudinal scanning of the arc attachment with its gas-dynamic and magnetic rotation allow providing the uniform wear of the electrode surface. The specific erosion value is about 1-3 $\mu$g/C. It is 3 times less than that of the stationary AC plasma torches with the rail-type electrodes, working at the same power level with arc currents about 900 A. That enables production of the 1 MW industrial plasma torch with the hollow cylindrical electrode assembly, with lifetime above 1000 hours at currents in the arc up to 100-200 A.

Conclusion
Results of experiment directed towards the increase in the lifetime characteristics of electrode units of the powerful high-voltage electric-arc AC plasma torches are presented. The solution to the problem of obtaining the uniform wear of a copper hollow cylindrical electrode achieved by the controlled movement of the arc attachment along the working surface was offered. Organization of gas supply in the near electrode area and application of alternating magnetic field ensured movement of arc attachment along the surface with average speed from 2 to 14 m/s. Arc current was about 47A and 84A. Gas flow rate in near electrode area was about 4.5 g/s. The findings of influence methods on the electric arc attachment by electromagnetic and gas-dynamic forces are presented. The erosion of a hollow cylindrical electrode reached only 3 $\mu$g/C that enables production of the electrode assembly with life time above 1000 hours at currents in the arc up to 100-200 A.

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