High voltage AC plasma torches with long electric arcs for plasma-chemical applications

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Abstract. Powerful AC plasma torches are in demand for a number of advanced plasma chemical applications, they can provide high enthalpy of the working gas. IEE RAS specialists have developed a number of models of stationary thermal plasma torches for continuous operation on air with the power from 5 to 500 kW, and on mixture of H₂O, CO₂ and CH₄ up to 150 kW. AC plasma torches were tested on the pilot plasmachemical installations. Powerful AC plasma torch with hollow electrodes and the gas vortex stabilization of arc in cylindrical channels and its operation characteristics are presented. Lifetime of its continuous operation on air is 2000 hours and thermal efficiency is about 92%, the electric arc length between two electrodes of the plasma torch exceeds 2 m.

1. Introduction

1.1. Plasma torches for plasma chemical applications

Apart from catalytic processes, non-catalytic high-temperature processes can be widely used in the future. Their main features are high rate of chemical reactions, conversion of feedstock and product selectivity [1]. For this effect, the powerful plasma torches may be used to produce thermal plasma, which is the energy source for chemical transformation. The main fields of application of high-power plasma torches in the chemical industry are solid waste gasification [2]; reforming of natural gas [3] and biogas [4]; radioactive waste processing [5]; plasma assisted combustion of fuels [6]. Thus, the thermal plasma can be regarded as a heat carrier medium [7] or chemical process feedstock (air [8], steam [9], CO₂ [10]). In any case, all these processes require high power, long continuous operation lifetime and plasma parameters constancy in industrial applications [11]. These problems limit an implementation of plasma-chemical technologies.

Effective thermal plasma sources are electric arc plasma torches (thermal plasma generators). The most widely used are direct current (DC) devices; overview of the various modern models is presented in [12]. Plasma torches operating in the power up to 20 MW have been designed. Continuous operation of plasma torches is limited by resource of electrodes, with the highest erosion occurring on the cathodes. The thermal efficiency of DC plasma torches usually does not exceed 80%, and the ongoing task of
improving their effectiveness does not lose its relevance. Overview of alternative current (AC) systems designed for industrial applications is presented in [13]. Power range is up to 3 MW. Working gases used for DC and AC plasma torches are Ar, He, N₂, H₂, Air, CO₂, CO, CH₄ and steam. Using AC allows reduction of specific electrode erosion, as each electrode is alternatively an anode or cathode and to achieve high performance resource factors and high thermal efficiency.

1.2. High voltage AC plasma torches and plasma chemical installations developed in IEE RAS

Single-phase and three-phase high-voltage AC air plasma torches (50 Hz) were developed and investigated in the Institute for Electrophysics and Electric Power of Russian Academy of Sciences (IEE RAS). These are devices with long electric arcs, burning in separate cylindrical channels with rod electrodes [14]. Power of three-phase plasma torches is up to 75 kW, channel length for different models is ~ 0.2 - 0.5 m. Life time of water-cooled rod electrodes of these devices is up to 200 hours. The operating current is up to 30 A, voltage drop is up to 1700 V, air flow rate is up to 35 g/s, thermal efficiency is 95% and average temperature is 1500 - 5500 °C. Single-phase plasma torches operate in the power range up to 15 kW with air flow rate up to 4 g/s [15]. The operating current of such devices is up to 10 A, voltage drop is up to 2000 V, thermal efficiency is ~ 95%, and life time is 300 hours.

A high-voltage multigas arc three-phase AC plasma torch (50 Hz) with power up to 150 kW, operating on such plasma-forming media as steam, air, carbon dioxide, methane, vapors of halogenated organic compounds, as well as various mixtures of these gases and vapors have been developed in IEE RAS based on the experience in the development of air plasma torches with rod electrodes. It also used the scheme with long arcs (up to 0.8 m), burning in the separate discharge channels with rod water-cooled electrodes. Operating parameters of multigas plasma torch working on mixture of steam and air in different ratios have been studied [16, 17]. Dependences of its power characteristics, thermal efficiency on the arc current, flow rate and composition of the plasma-forming mixture were determined. Steam flow rate is 3.55 - 5.8 g/s, air flow rate is 1 - 3 g/s, arc current is 28 - 29 A, arc voltage drop is 1.15 - 1.85 kV, power is 57.6 - 87.5 kW, thermal efficiency is 94.3 - 95.3%. Also the parameters of the electric arc column (average for the arcing period) are determined, such as arc length (~ 0.8 m), bright arc core diameter (~4.47 mm), arc column temperature (10.0 - 11.5) ×10³ K, electric field strength (14 - 23 V/cm), Paper [18] presents the investigation results of the plasma torch operation on H₂O/CO₂/CH₄ mixture under constant flow rates of steam (3 g/s) and carbon dioxide (3 g/s) and with methane flow rate varying from 0 to 0.8 g/s. Operating characteristics depending on arc current, flow rate and composition of plasma forming mixture were obtained. Arc current is 52 - 59 A, arc voltage drop is 0.87 - 1.13 kV, power is 77.7 - 114.6 kW, thermal efficiency is 93.8 - 95.9%, average temperature of plasma is (3.2 - 3.3) ×10³ K. Life time of continuous operation of electrodes is 200 hours. Also the parameters of the electric arc column (average for the arcing period) are determined, such as the length (~ 0.6 m), bright arc core diameter (5.99 - 7.54 mm), arc column temperature (8.3 - 10.5) ×10³ K, electric field strength (14 - 22 V/cm).

The developed AC plasma torches were tested on IEE RAS pilot plasma chemical installations for gasification of solid waste and reforming of gaseous hydrocarbons. Air plasma torches with rod electrodes worked in the downdraft gasifier during investigation of air gasification of wood waste. Thus, due to the heat of plasma the syngas quality was considerably improved in comparison with autothermal gasification: content of combustible components (H₂ + CO) in the product gas was 55 – 67%, nitrogen was 26 – 36%; LHV (lower heating value) of syngas was 5.9 – 7.2 MJ/Nm³; content of tars was 50 mg/m³. Air plasma gasification of organic solid matter flows at relatively low specific energy consumptions (2.4 – 3.2 MJ/kg). The experimental results are represented in [19].

Similarly, the multigas plasma torch worked with the plasma-chemical reactor for the methane reforming by steam and carbon dioxide [20]. Due to flexible regulation of the plasma-forming medium composition without shutting down the torch and change the power supply settings it was possible to obtain synthesis gas with H₂/CO ratio of 1 to 2.4. Hydrogen and carbon monoxide selectivities were 98%, the methane conversion was 99%, acetylene and soot content did not exceed 0.1 %vol. and
125 mg/Nm³ of synthesis gas respectively. Specific power consumption of the process depends on the plasma forming gas composition: for steam/carbon dioxide reforming is 37.5 MJ/kg of converted methane; for dry reforming is 48.3 MJ/kg of converted methane.

High temperature of the electric arc does not only have a positive effect on working gas heating, but also introduces a number of limitations on usage of some design concepts. Rod electrodes have good resource characteristics when operating on air with currents do not exceeding 30 A. When operating from the AC power supply (50 Hz) with no-load voltage of 10 kV it was possible to obtain a steady burning arc with voltage drop of 3 kV. Investigations on development of electrodes with a long life time at high currents (up to 100 A) were carried out in order to create a plasma torch with power more than 150 kW. Such characteristics when operating on alternating current were obtained on cylindrical electrodes with internal working surface (hollow electrodes). The operation of experimental models of hollow electrodes was investigated to determine the possibility of increasing the resource. The modes allowing distribute thermal impact at controlled movement of the electric arc spot along electrodes surface under the influence of gas dynamic forces and magnetic field were determined. [21, 22].

Investigations on the experimental installation equipped with supply systems, mass flow controllers for plasma forming gases, acquisition of electrical parameters, high-speed video and spectral diagnostic equipment were carried out to create a powerful plasma torch. A series of experiments for different power levels and air flow rates were performed. The powerful AC plasma torch with hollow electrodes was developed on the basis of obtained experimental data. Its characteristics will be presented below.

2. Experimental setup for investigations of AC electric arc systems with hollow electrodes

The operation of single- and three-phase experimental models of plasma torch with hollow electrodes was investigated to obtain characteristics for the high power plasma torch development. Electric field strength of the arc column at low current (up to 10 A) in 10 kW air plasma torch is about 30-40 V cm⁻¹, but one is only 7-11 V cm⁻¹ for electric arcs with current of about 80 A. When operating at current of about 80 A to produce a high arc voltage drop it was required to increase the length of the channels (up to ~ 1 m). Photo of running experimental single-phase model of the plasma torch with the long discharge channels and various designs of hollow electrode units is presented in figure 1.

![Figure 1. Experimental single-phase model of high-voltage AC plasma torch. (a) Photo of operation, (b) schematic diagram of device. 1 – Power supply; 2 – case; 3 – arc; 4 – electrode; 5 – solenoid; 6 – diagnostic window; 7 – terminal for power supply connection; 8 – tangential working gas flow.](image-url)
The single-phase electric arc has spots on two electrodes disposed in separate channels. The position of the arc spot and arc column around the electrodes is controlled by the magnetic field and the swirling gas flow. Most part of the arc column length is located along the axes of the discharge channels and its small section in the external space. So the electric arc length between two electrodes of experimental model is about 2.5 m (1 m + 1 m in channels + ~0.5 m outside).

The measuring installation including electrical probes, acquisition system for AC high voltage signals measurement with a sampling rate of no less than 10 kHz was created to determine the strength of the electric field in different areas of the arc column and plasma parameters. Testing of elements of the measuring system with video recording was carried out.

Burning of arcs in channels at three-phase operation mode is the same as at single-phase, the arc columns at the outlets of three channels are closed to each other in the surrounding area. High-speed video and photo shooting were used to investigate the character of electric arcs burning at the outlet of the channels. The schematic diagram of three-phase AC plasma torch and arrangement of photo and video cameras are presented at figure 2 (a). The arcs at the channel outlets are represented at figure 2 (b) – photo from side camera (9-S at schematic diagram), figure 3 (a) shows the arc in the near electrode area (rear view camera 9-R).

![Figure 2](image-url)

**Figure 2.** (a) Schematic diagram of high voltage three-phase AC plasma torch with hollow electrodes. (b) Photo of electric arcs outside the channels – side view, contour line indicates boarders of front part of the plasma torch and outputs of channels (shutter speed 1/8000 s). 1 – Power supply; 2 – case; 3 – arc; 4 – electrode; 5 – solenoid; 6 – diagnostic window; 7 – terminal for power supply connection; 8 – gas supply; 9-R, 9-S and 9-F – photo/video camera position (rear, side and front view accordingly); 10 – data acquisition system.

Arc column has a relatively small diameter of the light emitting area in the cold air flow at the electrode surface, the arc within the channels burns in the axial area and has a larger diameter. It is evident that the arc just in front of the channels outlet also has a relatively large diameter (in the picture looks fuzzy), but at the longer distance from the case, the part of the arc column captured by the transverse gas flow is contracted. Figure 3 (b) shows a photo of the electrode working surface.
3. High power three-phase plasma torch with hollow electrodes

The powerful three-phase AC air plasma torch with hollow electrodes operating in the power from 150 to 500 kW was developed on the basis of the performed experiments. Photo of the plasma torch is shown in figure 4.

![Figure 4. High-voltage AC plasma torch. Operation power 390 kW.](image)

This is a device with gas vortex stabilization of the arc in cylindrical channels. The electric arc length between two electrodes of the plasma torch is about 2.5 m (1 m + 1 m in channels + ~ 0.5 m outside, as shown at figure 2 (a)). It allows working with a high arc voltage drop (~ 2 – 3 kV) at relatively low currents (no more than ~100 A) what favorably affects the lifetime of electrodes. The operation principle of the plasma torch is the following: arcs stabilized by the swirling gas flow burn in separate cylindrical channels, close on each other at the outlet of the case. The arc spots are continuously rotated along the inner surface of the hollow electrode. Continuous scanning of the arc spots along the electrode surface in up-stream/down-stream directions is carried out to increase the life time of electrodes (simultaneously with the arc spot rotation). Preliminary short-term tests of plasma torch operation (~ 5 minutes) with
power up to 500 kW (103 A, 2900 V) were performed. Characteristics of plasma torch were obtained during long-term tests (more than 30 minutes for each mode) for the arc current up to ~85 A (up to ~410 kW). The thermal efficiency of the plasma torch is ~92%.

Life time tests of the plasma generator were carried out, performance characteristics were obtained. Figure 5 shows the static volt-ampere characteristic (VAC) of the arc, burning in the plasma torch at air flow rate of 65 g/s.

![Figure 5. Static VAC of the arc of high power AC plasma torch with hollow electrodes.](image)

The curve has a falling character, which is due to dropping VAC of the power supply system. The power of the plasma torch varies from ~200 to 330 kW at concerned current range. Possibility of significant changes in power at fixed flow rate of the plasma-forming medium and at the expense of the current change allows control of the specific energy consumption over a wide range.

Figure 6 represents the dependences of arc voltage drop and power versus air flow rate for arc current of ~85 A. The RMS values of arc current and the voltage drop on the arc and the active power of plasma torches were automatically calculated during operation on the instantaneous values of currents and voltages. Apparently, the arc voltage drop and power with increasing of air flow rate significantly increase. This is due to increasing of the intensity of heat exchange of the gas flow with the electric arc. Increasing in the heat exchange intensity causes cooling and contraction of the arc column, leading to the increase in current density and reduction in electroconductivity.

Figure 7 shows the dependences of enthalpy and average temperature of plasma versus air flow rate for the same operational modes of the plasma torch.

![Figure 6. Power and arc voltage drop of high power AC plasma torch with hollow electrodes.](image)

![Figure 7. Enthalpy and average temperature of plasma of high power AC plasma torch with hollow electrodes.](image)
These charts illustrate the flexibility and possibility of operational management of plasma flow rate and its enthalpy in a wide range. That may be useful for controlling of the plasma-chemical processes parameters.

Figure 8 shows the presented frames of high-speed shooting of high-power plasma torch operation (front view). Diffuse and contracted areas of the arcs at the channel outlets are visible. More bright arcs can be seen in the moments of current peaks, less bright arcs are observed at transition of the corresponding phase current through zero.

![Arcs of AC plasma torch with hollow electrodes. Frames of high speed video (frame rate 4000 fps, the exposure time of each frame is 2 μs). Each frame has its number on the left, time from start of record is on the right.](image)

The life time of electrodes determined as a result of certain tests at current of 83 A was about 2000 hours. Erosion of electrodes on the results of weighing after the first 50 hours of operation was $1.1 \times 10^{-6}$ g/C, then its value gradually increased and stabilized at a value of $3.3 \times 10^{-6}$ g/C at 180 hours of operating time of the electrodes. Then the erosion did not increase. The pattern of wear of the electrodes with current 83 A is shown above in figure 3 (b).

4. Conclusions

AC plasma torches with long electric arcs have good performance characteristics and are promising for the plasma-chemical applications. The usage of these devices as part of the pilot plasma chemical plants ensured the success of the experiments on the air plasma gasification of organic substances. For wood waste the content of fuel gas ($H_2 + CO$) in the products was 55-57%.

The AC plasma torch with power up to 500 kW has been developed. Its operation with arc currents up to ~85 A and power up to 410 kW was investigated. Organization of the long arc burning in the plasma torch channels with voltage drop of 2800 V allows operate with a relatively low current and obtain service life of ~2000 hours on air.

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