PLASMA PHYSICS AND PLASMA METHODS

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# Study of the dynamics of arc discharge burning in the methane-hydrogen-containing atmosphere in the alternating current plasma torch

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***The results of the study of the dynamics of arc discharge burning in the electric arc chamber of an alternating current plasma torch with the power of up to 10 kW are presented. The measurements were carried out using graphite and tungsten electrode tips at the atmospheric pressure in the following ranges of plasma-forming gas flow rates: $H_2$ up to 0.08 g/s and mixture $H_2$+$CH_4$ up to 0.1 g/s. Characteristic stages of discharge development were established, among which contracted, diffuse including formation of a plasma plume, and transient types of arc discharge were observed.***

*Keywords:* plasma torch; alternating current; arc discharge; high-speed video recording.
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## Introduction

The study of arc plasma burning modes is one of the most important tasks of modern low-temperature plasma physics. Due to their unique properties, such as high temperature and energy density, arc discharges are widely used in various fields of science and technology, including metallurgy, welding technologies, coating technologies, plasma chemistry, powder material production technologies, etc. Despite the number of papers [1–5] devoted to the study of arc plasma, some aspects of its behaviour remain underexplored.

Being widely used in industrial processes, plasma torches require a deep understanding of the mechanisms for the arc discharge to form and exit stably. Traditional diagnostic methods based on measuring electrical parameters are often not enough to fully describe the dynamic pattern of arc burning, especially under conditions of rapid temporal and spatial changes. High-speed photo and video shooting is an effective means of visualizing and analyzing arc burning processes in the discharge chamber. This method allows recording instantaneous changes in the arc structure, following its movement and deformation, and identifying key mechanisms of plasma interaction with surrounding surfaces. Modern digital cameras with high resolution and frame rate allow a detailed analysis of temporal and spatial

characteristics of the arc discharge, which is critical for understanding and optimizing the operation of plasma torches.

Due to their ability to generate high-enthalpy gas flows, plasma torches during plasma-chemical synthesis intensify chemical processes in the gas phase while the reaction zone and size of the process equipment become much smaller and the yield of the useful product grows.

The electric arc that occurs between the electrodes in the plasma torch chamber creates conditions for the high-temperature plasma to form. The main parameters that influence the arc burning dynamics include temperature, current density, gas pressure and components composition of the plasma-forming medium. The arc combustion dynamics influences the uniformity of distribution of the temperature and concentration of active particles in the plasma volume. Inhomogeneous distribution of these parameters can lead to uneven chemical reactions and, as a consequence, to a decrease in the yield of target products. For this reason, the optimization of these parameters allows achieving maximum efficiency of plasma-chemical processes and increasing the yield of useful products.

The goal of this paper is to study the processes of arc discharge formation and development using photo and video shooting methods. This will allow establishing the temporal and spatial characteristics of the arc discharge, such as shape and dimensions of the arc channel, radiation intensity, etc. The measurements were carried out using graphite and tungsten electrode tips at the atmospheric pressure in the following ranges of plasma-forming gas flow rates: $H_2$ up to 0.08 g/s and mixture $H_2$+$CH_4$ up to 0.1 g/s. Plasma torch operating modes have been analyzed, and arc burning modes have been described.

## Experimental unit and measurement methods

The studies were carried out using the experimental setup, which scheme is shown in Figure 1 and which comprises an alternating current plasma torch [6, 7], a power source, a plasma-forming gases cooling and a supply system, as well as a set of measuring instruments.

The plasma torch includes two housings made of 12X18N10T stainless steel. Each housing contains a water-cooled electrode unit with replaceable graphite output inserts. The electrode unit consists of a water-cooled housing and an electrode with a tip fixed to its end. The tip can be made of various materials, such as tungsten, graphite or copper. The housing has a channel for tangential supply of plasma-forming gas, which forms a spiral gas-vortex flow the cools and stabilizes the arc channel. A flange fixed to the nozzle unit that makes a space between the housing and inner wall for feeding the cooling water that ensures heat removal from the arc ignition zone. The electrode channels are arranged coaxially and connected to the electric arc chamber, which can operate as a reaction chamber acting as a plasma-chemical reactor when the material to be processed is added.

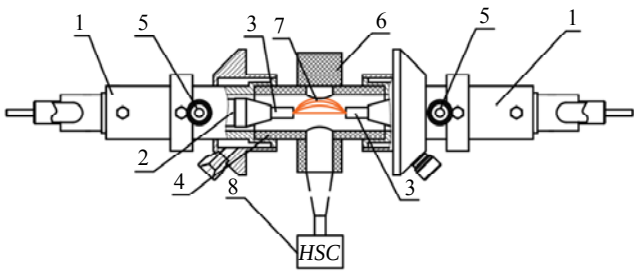


***Fig. 1. Schematic view of the plasma torch and observation method using high-speed photo and video shooting: 1 – housing; 2 – electrode; 3 – tip; 4 – sleeve; 5 – gas supply; 6 – electric arc chamber; 7 – arc; 8 – high-speed chamber***

With the high voltage supplied between the electrode and the inner wall of the channel, the electrical breakdown of the interelectrode gap occurs, which results in arc formation. Forced by the tangential gas flow supplied into the channels, the arcs move to the electrode ends, then they move along the graphite insert, are blown out onto its end and are connected to the electrode from the opposite channel. Thus, the arc spreads from the end of one electrode to the end of another one. When the polarity changes, the same things occur on the other electrode. Formation of the vortex gas flow in the channels facilitates the efficient removal of excess heat from the central arc, thus preventing temperature gradients and associated instabilities of the plasma channel from being developed.

It should be emphasized that plasma-forming gases can be mixed in the plasma torch of this type without the need to stop and additionally readjust the device. This feature allows conducting various experiments, thus significantly reducing time and material amounts. To ensure the guaranteed ignition the device was started using argon with the flow rate of up to 0.5 g/s. Upon reaching a steady state, hydrogen was supplied within the operating flow rate range, while the argon supply was stopped. Later ballast gases were not used to maintain discharge burning.

High-speed shooting was carried out using Citius imaging High Speed Video Camera arranged perpendicularly to the plasma torch axis. The camera is capable of shooting at up to 4000 frames per second (fps) in high resolution. The proper interfaces allow connecting the camera to a personal computer, which enables the remote control of shooting settings and real-time monitoring of the shooting process. This recording method allowed locating the arc and conducting the detailed analysis of the temporal and spatial characteristics of the arc discharge.

## Findings and discussion

As part of the research performed, a number of experiments were carried out using photo and video shooting. The hydrogen flow rate varied up to 0.08 g/s, methane flow rate – up to 0.02 g/s, and the plasma torch power varied within the range of up to 10 kW; the total duration of the experiment did not exceed 30 minutes.

The analysis of the measurement results considered both static characteristics reflecting the time-averaged ratios of changing parameters and dynamic characteristics associated with changes in the arc burning process over time. The arc burning dynamics were recorded by means of the corresponding oscillograms: the current change over time was sinusoidal, and the voltage curve exhibited distinct ignition and extinction peaks when crossing zero.

The total duration of the voltage change half-period on the oscillogram can be divided into three parts. The first and third parts correspond to the lateral sides of the trapezoid – these are the stages of voltage increase and decrease in the interelectrode gap, when the arc discharge has not yet formed or has already ceased to exist. The middle part, which can be called the trapezoid “base”, is characterized by voltage fluctuations around the average value and corresponds to the arc discharge lifetime. In some half-periods, a slight increase in voltage is observed closer to the middle of this interval. The amplitude magnitude of peak voltage fluctuations varies depending on the gas type and is within the range of 1.2 to 4 kV.

The result of high-speed video shooting of the discharge in the electric arc chamber of the plasma torch were files of the .avi format, which reflect the dynamics of various modes of the arc discharge under study. To clean the frames from the noise, which existed as constantly glowing areas near the electrodes, the .avi files were filtered. Among all the file frames, there was one whose integral

luminosity of the frame was minimum, that is, when the discharge was obviously absent. Next, the matrix of the frame with the minimum luminosity was subtracted from the matrix of each frame of the file. The result was a new .avi file with minimum noise. The new files provided were processed as follows. The sum of all matrix pixels with a resolution of [320×306] of the next *j*-th frame was calculated. The result of summing was written to the *j*-th position of the new vector, the length of which corresponded to the number of frames in the .avi video file. According to this procedure. the dependence of the relative luminosity intensity on time was calculated for all the discharges under study. The relative luminosity intensity can be assumed to correlate well with the calculated discharge current power. Using the resulting vector of relative luminosity intensity of the discharge under study, the frequency characteristic of the process was determined using the Fourier transform "fft". For all discharge types, the fundamental frequency was 100 Hz with minor satellite frequencies that were multiples of the fundamental frequency.

The figures show successive frames from the video files recorded with Citius high-speed camera with the video shooting rate of 4000 frames per second and exposure of 10 μs normal to the discharge plane. The frames show the electrode tip, from its material (tungsten and graphite) is torn out and carried away with the plasma flow upon application of the current pulse. The frames were selected as follows: with reference to the previously derived vector of relative luminosity intensity, the successive frames were selected, starting with the minimum value of the discharge luminosity, that is, from the discharge start until the maximum luminosity intensity was reached, and then frames with the decreasing discharge luminosity intensity were selected until the given discharge period extincted. The right inset in Figure 2 shows an example of a transient discharge, where the points on the discharge intensity curve mark the selected frame numbers from the video file, starting with number 235. The frames were selected similarly from the corresponding video files of other categories for Figures 3 and 4.

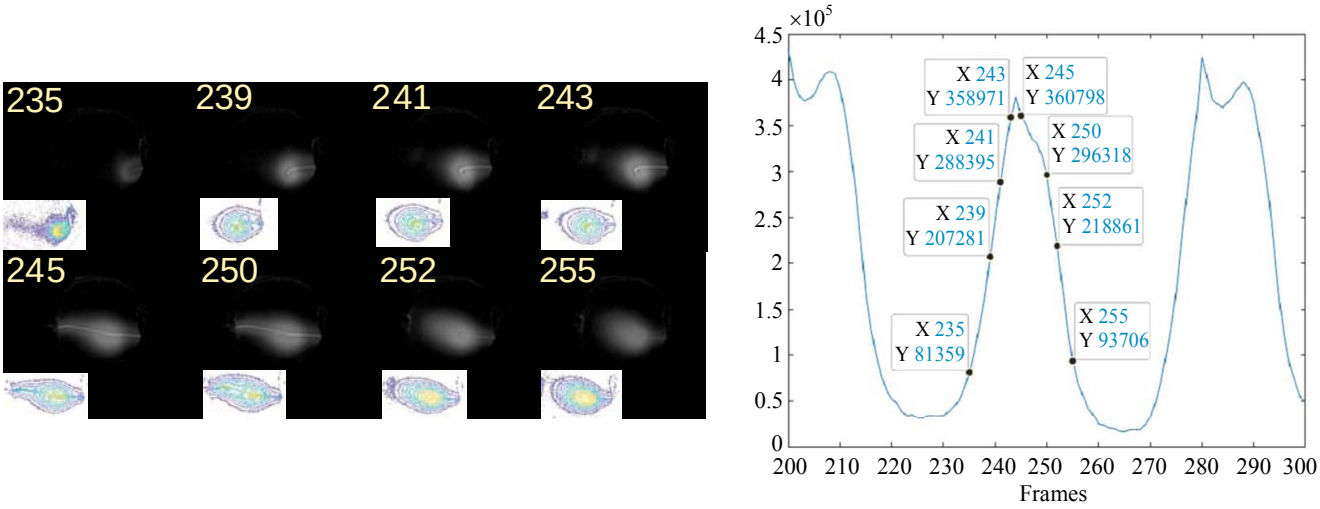


***Fig. 2. Transient discharge mode with a pattern of radiation intensity distribution depending on the frame number, flow rate of hydrogen $H_2$is 0.06 g/s, current is 6 A, power is 6 kW***

Figure 2 shows the pattern of the transient discharge developing, including the initial formation of a plasma cloud near the electrode, where the arc ignites (forms), without reaching the opposite electrode it bends (extends) to the end of the electrode

and is blown out by the plasma-forming gas flow towards the opposite electrode. After the maximum intensity values (frames 245 and 250) are reached, the arc moves back to the electrode where it was ignited. Note that a plasma cloud is observed around the arc tip at all stages. The diameter of the plasma cloud reaches 25–30 mm. This mode is observed at the plasma-forming hydrogen gas flow rate up to 0.06 g/s, in case of short heating of the electric arc chamber for several minutes and after reaching a steady-state mode, as well as in case of hydrogen-methane ratio of 6:1 during the first minutes of operation.

The contracted discharge is shown in Figure 3. It is typical for the hydrogen flow rate of 0.04–0.08 g/s and is observed in case of the "cold" chamber. Almost immediately, a clearly defined arc is formed, where the pressure of the self-magnetic field exceeds the gas kinetic pressure, thus resulting in contraction. As the discharge develops, an increase in the arc cross-section is observed. This may depend on the change in the pressure ratio of the self-magnetic field and gas-kinetic field in the favor of the latter's pressure. This can also explain the gradual curving of the arc by the working gas blown out.

Note that both the arc initiation (frame 145) and extinction in this half-period under consideration (frame 180) originated from the right electrode. In the next half-period, with the polarity changed on the electrodes, the arc ignites on the left electrode (frame 186). The weak section of the arc can also be noticed around the opposite electrode. No arc radiation was observed between these areas. The sensitivity threshold of the video camera receiver is most likely to be lower than the arc luminosity in this area and it is not enough for being recorded. It can be assumed that if we used a more sensitive colour photodetector matrix, we could examine R, G and B matrices of this frame individually to see this area, probably, in more details.

Figure 4 shows the pattern of the discharge development referred to in the foreign scientific literature as a plasma plume [8, 9] (plasma cloud). Gas-dust plasma clouds were often observed during the experiments with arc discharges on graphite electrodes, a gradual expansion of plasma plume from frame to frame to occupy the half-space up to the middle of the interelectrode distance, which was ~30 mm. After the maximum luminosity of the discharge was reached, which corresponds to the maximum power (frames 241 and 244), the reverse process of plasma cloud contraction occurs until it completely extincts. It should be noted that there is a region of increased brightness in the near-electrode space, which resembles a forming arc; however, as can be seen from the lines of equal intensity, no clearly visible arc can be observed. The presence of a plasma cloud could only be recorded by mixing two types of plasma-forming gas, methane and hydrogen, in the ratios of 1:8, 1:6, 1:3. The main gas, hydrogen, was varied in the range of 0.06 g/s to 0.08 g/s, then methane was mixed into it at the rate of 0.01 g/s.

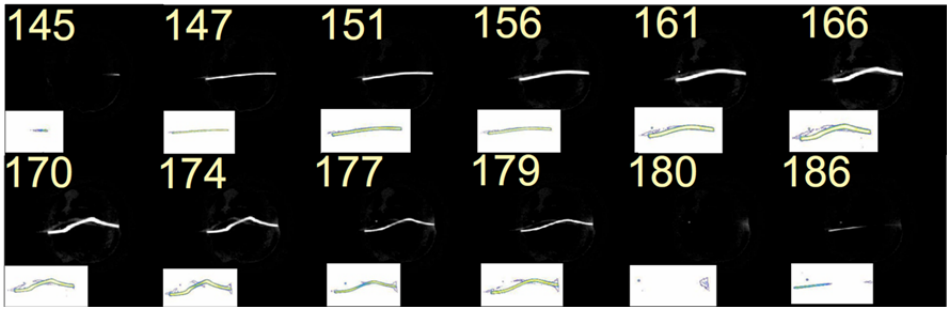


***Fig. 3. Contracted discharge mode, flow rate of hydrogen $H_2$ is 0.06 g/s, current is 6 A, power is 6 kW***

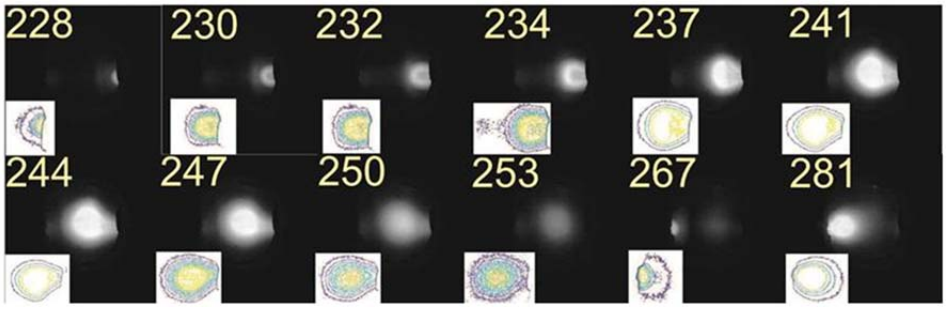


***Fig. 4. Diffuse (plasma plume) discharge mode, mixture flow rate: hydrogen $H_2$ – 0.08 g/s and methane $CH_4$ – 0.01 g/s, current is 6 A, power is 7 kW***

Considering that the setup was not changed during the experiments, the changeover from the intermediate (transition) discharge, with the plasma cloud formed at first near the electrode, to the contracted one and then to the plasma plume (plasma cloud), the different nature of the discharge can be explained by the ionization degree of the working gases used in the experiment and by the pressure difference.

## Conclusion

The paper analyzes the burning dynamics features of arc discharge at the atmospheric pressure in the ranges of plasma-forming gas flow rates: $H_2$ up to 0.08 g/s and mixture $H_2$+$CH_4$ up to 0.1 g/s in the alternating current plasma torch. Characteristic stages of discharge development were established, among which contracted, diffuse including formation of a plasma plume, and transient types of discharge were observed. Contracted discharge is typical for the hydrogen flow rate of 0.04–0.08 g/s with a clearly defined arc body formed. The transient discharge mode was recorded at the flow rate of the plasma-forming gas, hydrogen, of up to 0.06 g/s and with the hydrogen and methane mixture ratio of 6:1; a plasma cloud with a diameter of 25–30 mm formed around the arc body was observed. The diffuse discharge mode with the gas-dust plasma plume occurring took place in the modes of methane and hydrogen mixture ratios of 1:8, 1:6, 1:3.

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