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Features of the dynamics of an alternating current electric arc and its parameters in an air-blown plasma torch

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The paper deals with the results of an experimental study of a single-phase plasma torch with ring electrodes operating in the power range of up to 10 kW. The experiments were conducted with varying plasma gas (air) mass flow rates up to 3.2 g/s. The study methodology included synchronous recording of arc discharge current and voltage waveforms, coupled with high-speed video recording of the electric arc. Based on the obtained data, the arc attachment character was determined and a comprehensive analysis of its temporal and spatial characteristics was conducted. Plasma temperature was estimated using optical emission spectroscopy based on the relative intensity of copper Cu I lines. Calculations revealed that the temperature in the arc discharge zone reaches values of approximately 7000 K.

Keywords: plasma torch, alternating current, air, plasma temperature.

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Introduction

The intensive introduction of plasma torches into modern industrial technologies dictates the need for an in-depth study of the fundamental mechanisms underlying the initiation and maintenance of the stability of the arc discharge. For an adequate reproduction of the complex spatiotemporal dynamics of arc burning, which is especially critical under conditions of fast-occurring and nonstationary processes, the dynamics of arc motion and their attachment points were recorded using modern high-speed digital cameras with high spatial and temporal resolutions. This approach makes it possible to obtain comprehensive information about the morphology of the discharge by recording in detail the instantaneous transformations of its structure and allowing the

trajectories of motion to be traced with high accuracy. This method of comprehensive investigation finds confirmation in works studying the zone of arc attachment to the anode [1, 2], where high-speed imaging acts as a key diagnostic tool, as well as in studies of prototypes of technological synthesis installations in an open air environment, demonstrating similar approaches to recording electrophysical parameters [3, 4]. The methodology of the analysis was based on comparing video recording data with the measured values of the electrical characteristics of the arc discharge – oscillograms of the instantaneous currents and voltage values.

As a theoretical basis for analyzing the collected data, the mathematical apparatus of spectral analysis based on the Fourier transform is used. The Fourier transform makes it possible to represent a complex signal as a set of harmonic

oscillations, enabling the identification of the dominant frequencies. Such an approach allows for a transition from the analysis of the temporal parameters of the signal to the study of its frequency composition. By analyzing the radiation intensity of the plasma, it is possible to reveal the relationship between the spatiotemporal changes in the brightness of the glow and the dynamics of electric arc formation.

The integration of these two approaches – direct visualization and spectral analysis – creates the basis for the development of a new diagnostic protocol. It makes it possible to compare the arc power calculated from the oscillograms of current and voltage across the arc, with its integral luminosity obtained from optical measurements under various video recording geometries.

The aim of the present work is a comprehensive experimental study of the dynamics of arc discharge development in air in a single-housing alternating current plasma torch.

Experimental Setup and Measurement Methods

The studies were carried out on an experimental setup schematically presented in Figure 1. This work is a continuation of many years of research by the author team in the field of designing and creating low-temperature plasma generators [5]. The setup includes an alternating current plasma torch [6], a power supply consisting of a power transformer of the type OS-100/6, and a measurement system. The plasma torch is connected to a system for supplying the plasma-forming gas (gas mixture), a cooling liquid, and is equipped with a unit for regulating and measuring their flow rates. In contrast to previous prototypes, the presented modification is distinguished by an optimized geometry of the interelectrode gap and the use of a gas-dynamic stabilization scheme containing three gas supply circuits for more effective confinement of the arc column.

The power supply of the plasma torch was controlled by an Advantech industrial microcontroller, which provides monitoring of the current and voltage oscillograms recorded by sensors. The air supply system included a manifold rack with pressure regulators for

individual adjustment of the gas supply to each circuit.

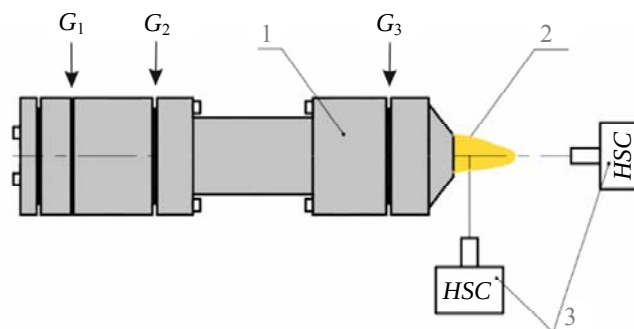


Fig. 1. Schematic view of the plasma torch and observation method using high-speed photo and video shooting: 1 – alternating current plasma torch; 2 – plasma torch plume; 3 – high-speed camera

The diagnostic technique included simultaneous recording of electrical parameters (current and voltage oscillograms) and optical diagnostics of the discharge dynamics. The recording of the electrical parameters of the arc was synchronized with high-speed video recording of the operation of the plasma torch in air (electrode gaps $D_1 = 1.9$ mm, $D_2 = 2.5$ mm) using a Citius imaging High Speed Video Camera.

The camera was positioned in two planes (Fig. 1): frontally to record the discharge inside the chamber and perpendicular to the axis to image the plasma plume at the exit cross-section. The recording was carried out at a frequency of 4000 fps with high resolution and data storage on a PC. This recording method made it possible to determine the location of the arc attachment and to carry out a detailed analysis of the temporal and spatial characteristics of the arc discharge from the time dependences of the plasma radiation intensity. The possibility of remote control of the camera ensured monitoring of the recording process in real time.

It was experimentally established that the studied type of plasma torch ensures stable arc burning and uninterrupted initiation of the arc discharge within the specified working gas flow rates. Analysis of the obtained data made it possible to obtain the electrical and energy characteristics of the setup over a wide range of operating parameters. The dynamics of arc burning is characterized by the corresponding oscillograms [6]. The power was also calculated

as the product of the instantaneous values of current and voltage, which depended on the mass flow rate of air and increased uniformly and linearly, in the range of 6.6–7.1 kW for flow rates of 2.5–3.2 g/s.

Findings and Discussion

The radiation of an arc discharge in an air atmosphere at normal pressure is predominantly continuous in nature, which is due to the high temperature of the arc plasma (6000–10000 K) and the dominance of bremsstrahlung and recombination mechanisms. This continuum, approximated by the Planck function, is superimposed by emission lines and bands of atoms and molecules, whose contribution to the total radiation energy does not exceed 30%. Analysis of the energy balance of radiation [7, 8] shows that the continuous (background) spectrum is the dominant component, while the contribution of the line-band spectrum is estimated at 10–30% of the total radiated energy. The energy distribution in the optical range at a voltage of 4 kV is characterized by the predominance of visible radiation, which accounts for up to 69% of the total energy of the optical spectrum. The energy emitted in the ultraviolet (UV) range is ~ 30%, whereas infrared (IR) radiation makes an insignificant contribution of ~ 1%.

Visualization and diagnostics of the arc plasma dynamics were carried out by the method of high-speed video recording. A camera was used whose photodetector array sensitivity was in the spectral range of 300–1050 nm, which made it possible to record the plasma radiation intensity and reflect oscillations of the arc column, extinction/restart, temperature fluctuations, and the arc shape. The recording was carried out at a frequency of 4000 fps, which, with a mains voltage period of 20 ms (50 Hz), gives a time resolution of 250 μ s per frame, i.e., 80 frames per period. These visual changes are related to changes in current and thermal power and, therefore, it can be assumed that, to a first approximation, they reflect the evolution of the plasma energy of the electric arc.

During high-speed video recording of the discharge process in the plasma torch, video files in .avi format with a resolution of 320×306 pixels

were obtained. For data analysis, preliminary filtering was carried out, after which the total brightness of all pixels in each frame was calculated. This made it possible to form a time dependence of the plasma glow intensity.

Figure 2 presents the obtained frame-by-frame images at different air pressures in the system: $P_1 = 0.4$ atm, $P_2 = 0.8$ atm, and $P_3 = 1.0$ atm, corresponding to the circuits for supplying the plasma-forming gas air, which are designated in Figure 1 as G_1 , G_2 , and G_3 . The horizontal axis (abscissa) shows the frame number, which is equivalent to time with a step of 250 μ s.

As can be seen from Figure 2, a gradual increase in radiation intensity is observed up to frame 421 and then a decrease to 436. Further in Figure 2: the second half-period (10–20 ms), during which a similar character of the radiation intensity dependence is observed. It is interesting to note the characteristic counterclockwise twisting of the arc from the attachment to the plasma torch housing. As can be seen from Figure 2, starting from frame 408 and up to and including 432, the arc attachment (the white point at the bottom of the frame) is stationary. However, for the second half-period, a different character of arc behavior is observed, which rotates quite intensively, and the attachment moves axially – frames 448 to the extinction of the arc at frame 481.

For the difference in the behavior of the electric arc attachment in different half-periods of the supply voltage of the plasma torch, the following explanation can be proposed. The ring-shaped electrodes used in this device are characterized by axial symmetry. As a consequence, the position of the electrodes corresponding to the anode and cathode relative to the plane of the exit nozzle changes vice versa every half-period. This leads to a change in the direction of arc ignition and, accordingly, the direction of the electric current in it. Obviously, the direction of the air flow remains constant, but in one half-period this flow coincides with the flow of electrons from the cathode (negative electrode) to the anode (positive electrode), while in the other, when the polarity changes, it is opposite. This serves as the reason for the difference in the behavior of the arc attachment and its rotation observed in different half-periods of the plasma torch operation. At the same time, such a design of the plasma torch has an

advantage over other devices, since it ensures reliable confinement of the arc on the surface of

the ring electrodes, preventing wear of the electrode edges.

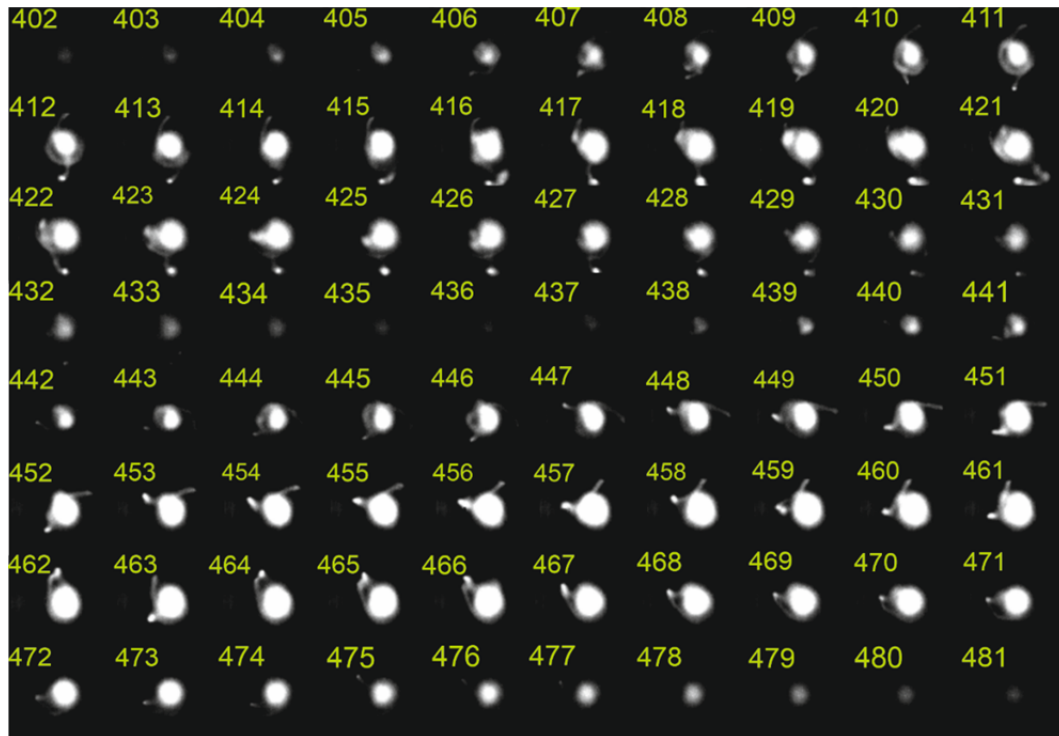


Fig. 2. Frame-by-frame images of the plasma plume over both half-periods: frames 402–441 – first half-period (positive); frames 442–481 – second half-period (negative)

Figure 3 presents the time-frequency characteristics of the arc plasma obtained from the radiation intensity using a high-speed video camera.

In the upper part of Figure 3, a difference in radiation intensity between the half-periods can be noted due to the change in the direction of arc ignition, i.e., the direction of the electric current. Accordingly, in the lower part of Figure 3 there is a frequency of 50 Hz reflecting the difference between the half-periods. The presence of a dominant frequency of 100 Hz confirms the operation of the plasma torch in each half-period. All the measured and processed time signals showed good correlation with the electrical power of the discharge.

The emission spectra in the range of 495–630 nm of the plasma jet at the exit cross-section of the plasma torch were obtained using an Andor Shamrock 303i spectrophotometer with the Andor Solis software. A diffraction grating with 600 lines/mm and a blaze wavelength of 500 nm was used. The slit width was 20 μm . From the intensity ratios of pairs of emission lines Cu I 510.554 nm transition $3d^9 4s^2 \rightarrow 3d^{10} 4p$ and 521.82 nm $3d^{10} 4p \rightarrow 3d^{10} 4d$ with statistical weights $g = 4$ and $g = 6$, respectively; 515.323 nm transition $3d^{10} 4p \rightarrow 3d^{10} 4d$ and 578.213 nm $3d^9 4s^2 \rightarrow 3d^{10} 4p$ with statistical weights $g = 4$ and $g = 4$, respectively, the temperature of the arc plasma was determined, which amounted to ~ 7000 K. Figure 4 shows the emission spectrum of the plasma jet at an air flow rate of 2.52 g/s.

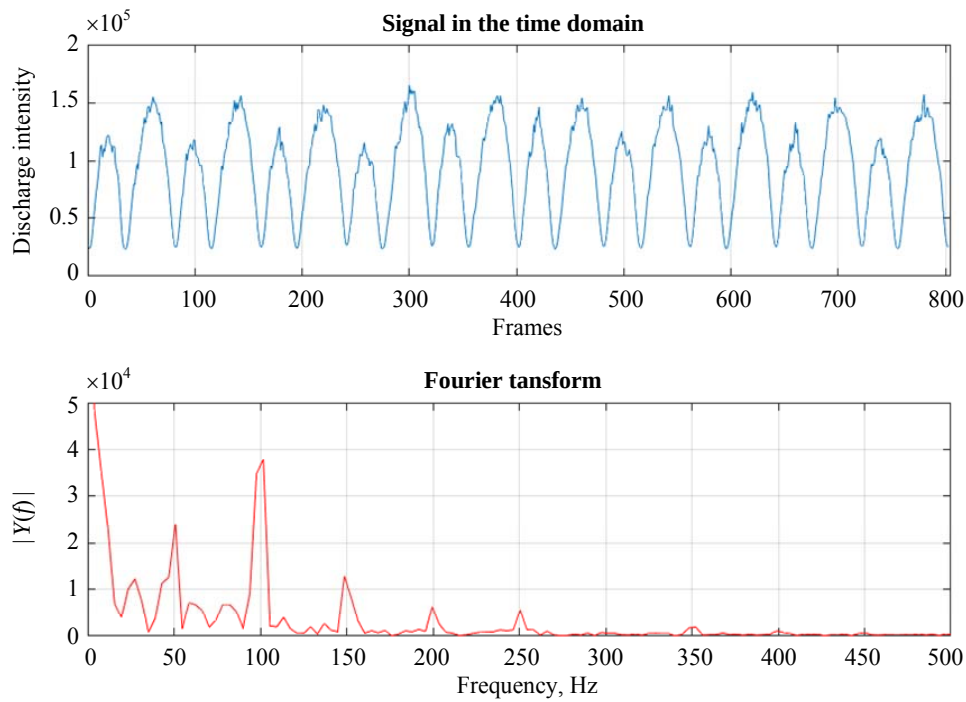


Fig. 3. Characteristics of the arc plasma: top – radiation intensity versus time over 10 full periods of the 50 Hz frequency (250 μ s per frame); bottom – frequency characteristic

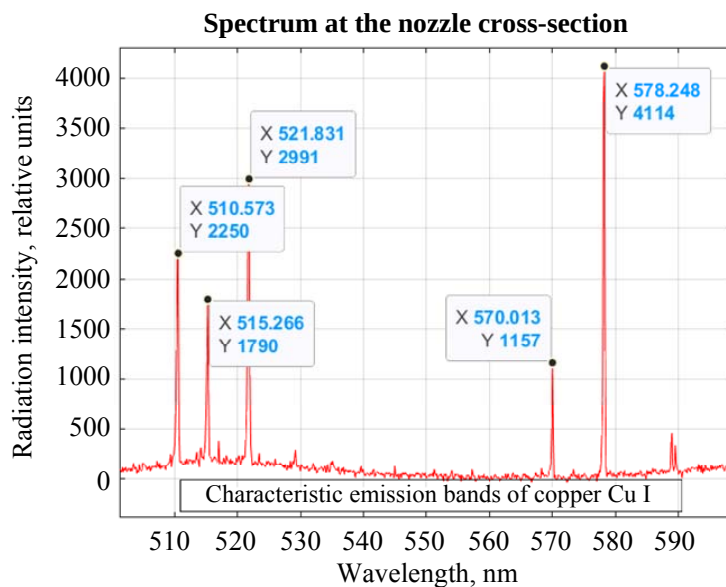


Fig. 4. Emission spectrum of the plasma jet at an air flow rate of 2.52 g/s

Conclusion

The work carried out a study of the discharge development processes in the plasma torch at two different positions of the high-speed camera. The characteristic counterclockwise twisting of the arc from the attachment to the plasma torch housing is noted, with the arc attachment being stationary.

However, for the second half-period, a different character of arc behavior is observed, in

which the attachment moves axially. During the analysis of measurements results we considered the dynamic characteristics related to changes in the process of arc burning in time, the value of arc power was calculated as product of instantaneous current and voltage values. The temperature of the arc plasma, which amounted to ~ 7000 K, was determined from the emission spectra of the copper lines Cu I.

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