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

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The paper deals with the results of a study of a single-phase plasma torch with ring electrodes with a power of up to 10 kW. The measurements were carried out using copper ring electrodes at atmospheric pressure with an air flowrate of up to 3.5 g/s. A study of the plasma torch discharge development was carried out at two positions of the high-speed chamber: the first – the main optical axis of the chamber coincided with the main axis of the plasma torch, the second – the main optical axis of the chamber is located perpendicular to the plasma jet at the exit from the plasma torch. Time dependences of the plasma radiation intensity inside the chamber and a free plasma torch were obtained. A comparison was made of the arc power calculated from the oscillograms of current and voltage with the observed plasma radiation intensity at the frontal position of the video camera. It was determined that the plasma radiation intensity reflects the evolution of the arc power with a correlation coefficient of ~ 0.96 .

Keywords: plasma torch, alternating current, arc discharge, high-speed video recording, correlation between plasma radiation intensity and arc power.

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Introduction

The widespread introduction of plasma torches into industrial technologies dictates the need for in-depth study of mechanisms of occurrence and maintenance of arc discharge stability. Standard diagnostic methods based exclusively on the assessment of electrical characteristics are often insufficiently informative for adequate reproduction of complex temporal and spatial dynamics of arc burning, especially under the conditions of rapidly changing processes.

Application of the newest digital cameras with high resolution and high frame rate provides comprehensive information about temporal and spatial features of the discharge, these methods

allow you to record in detail instantaneous transformations of arc structure, trace trajectories of its movement.

The analytical approach proposed in this work is based on invertibility property of Fourier transformation making it possible to identify the relationship between main infrequencies of spectral decomposition and characteristics of signal itself. By analyzing the intensity of plasma radiation, it becomes necessary to identify the relation between spacial-temporal changes of light brightness and internal mechanisms of electric arc formation. For this purpose, it is convenient to use the properties of Fourier transformation which is able to represent the signal (for example, change of radiation intensity) as a set of harmonic oscillations of different

frequencies. One of the key conclusions of the theory is that if the main component of the spectrum of two functions coincide, the functions themselves are quite close within the first approximation. In other words, the nature of the change in the main component of the plasma radiation spectrum is closely related to the development features of an electric discharge.

Practically this means that by measuring the distribution of frequencies in the plasma radiation intensity spectrum, you can indirectly judge the parameters of the electric arc itself, such as current strength, voltage and plasma temperature. Thus, establishment of such dependency makes it possible to create an effective diagnostic tool for the state of the plasma torch during operation.

The purpose of this paper is to study the processes of discharge development in plasma torch at two different positions of a high-speed camera and to conduct a comparative analysis of the arc power calculated according to the current oscillograms and voltage with the observed intensity of plasma radiation. Measurements were conducted using plasma-supporting gas – in the flow range from 0.84 g/s to 1.75 g/s at atmospheric pressure.

Experimental unit and measurement methods

Experimental setup included a single-phase AC current plasma torch with ring electrodes, electric power source, water cooling system, plasma-supporting gases supply system and measuring complex.

The operating plasma torch is shown in fig. 1. The key structural feature of the presented plasma torch is rejection of the traditional solid body that distinguishes this design from similar devices [1–3]. Single-phase plasma torch is a combination of joined ring-shaped electrodes made of copper grade M1 and M2. To provide visual observation of the arc development inside the plasma torch, electrode 1 is equipped with inspection window attached to it with mounting flange. Flange has a hole for a nozzle, its internal design creates a circuit for supplying plasma-supporting gas – circuit 1.

Electrodes 1 and 2 are connected via insulating flange with tangential ring for gas supply – circuit 2. Similarly, on the opposite side, electrode 3 is attached to electrode 2, creating one more circuit for gas supply – circuit 3. The size of interelectrode gaps between electrodes 1 and 2 and 2 and 3 can vary in the range from 0.1 to 3 mm. The external surface of electrode 2 is equipped with welded shell with connection pipes, making up cooling water jacket. The tightness of the structures is provided by rubber seals preventing the plasma-supporting gas and cooling liquid outside the plasma torch.

When a high voltage is applied to electrodes 1 and 3 of the plasma torch, an electrical breakdown of the interelectrode gaps occurs, which sequentially occurs between electrodes 1 and 2 and then electrodes 2 and 3. The result is the formation of two independent electric arcs.

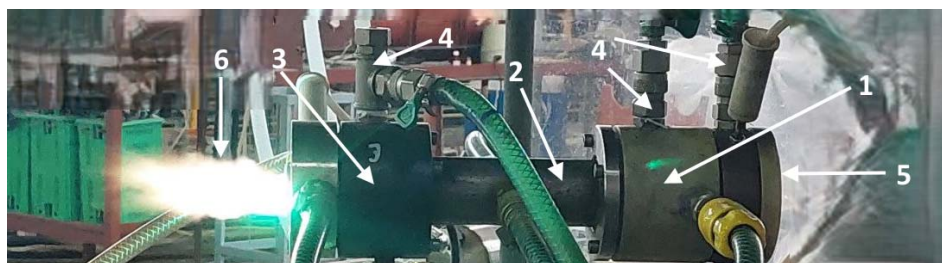


Fig. 1. Photo of working plasma torch with ring electrodes: 1 – electrode 1; 2 – electrode 2; 3 – electrode 3; 4 – gas supply circuits; 5 – inspection window; 6 – plasma jet

The movement of arc is attributed to the action of plasma-supporting gas introduced tangentially to the supply circuits, as well as the combined action of electrodynamic and gasdynamic forces. Under their influence the

reference points of arcs begin to move along the surface of the ends of electrodes causing gradual deformation and elongation of arcs bringing them close together. Gradually the arcs close, merging into one electric arc extending from electrode 1 to

outlet nozzle of plasma torch where the arc joint point is localized at the outlet edge of the nozzle. The merged arc continues its propagation along the axial direction of the plasma torch channel, smoothly lengthening and escaping the nozzle, ensuring the operation of device.

Power supply control is based on the application of Advantech industrial microcontroller allowing to monitor the current and voltage oscillograms, instantaneous values of currents and voltages are recorded using current and voltage sensors included in the power supply system. Air gas supply system included a collector rack with installed pressure regulators with pressure gauges ensuring the possibility to adjust gas supply to each of the circuits.

The recording of current and voltage oscillograms of electric arc was conducted simultaneously with high-speed video filming of single-phase plasma torch with ring electrodes and installed gaps $D_1 = 1.9$ mm and $D_2 = 2.5$ mm in air using Citius imaging High Speed Video Camera that was fixed in two positions relative to the plasma torch main axis. In the first case, the main optical axis of the camera coincided with the main plasma torch axis, namely, there was a frontal fixation of discharge inside the plasma torch discharge camera. In the second case the main optical axis of the camera was perpendicular to the main plasma torch axis and the camera recorded a plasma jet at the plasma torch outlet.

Time dependencies of the plasma radiation intensity inside the chamber and free plasma torch were obtained. The camera recorded high resolution video at 4.000 frames per second (fps) and was connected to the PC. Video files of plasma were recorded into computer memory for further processing. This registration method made it possible to determine the method of arc binding and conduct the detailed analysis of the temporal and spatial characteristics of the arc discharge.

Findings and Discussion

Electric arc in the air at atmospheric pressure is a stable electric discharge which is accompanied by a very bright glow. The arc occurs between electrodes at high current strength and relatively low voltage [4]. Temperature of the arc column can reach 4000–10000 K, which creates a spectral radiation continuum that is similar in the shape to the blackbody spectrum at

similar temperatures due to strong bremsstrahlung and recombination radiation. It can be noted that at atmospheric pressure the radiation spectrum of electric arc is close to continuous overlaid with linear (band) spectra of atoms and molecules. Wavelength of the broad maximum and general spectrum shape are often well approximated by Planck's law.

It should be noted that the radiation intensity integral over all wavelengths makes a greater contribution compared to linear-band spectrum, the contribution of which is 10–30 % of the total radiated energy [5, 6]. In the same study it was noted that the UV radiation energy from electric arc at a voltage of 4 kV is 30 % of the energy radiated as optical emission. The prevailing share falls on the photon energy of visible light – up to 69 %. The infrared radiation energy is very small and is only 1 % of the total energy in the spectrum range.

Considering spectral sensitivity of Citius imaging video camera used in work which is limited from 300 to 1050 nm with a broad maximum at 450–750 nm, high-speed shooting gives information on the plasma radiation intensity and reflects fluctuations in the arc column, attenuation/restart, temperature fluctuations and the shape of the arc. These visual changes are related to changes in current and thermal capacity and that is why we can assume that in the first approximation they reflect the evolution of the plasma energy of the electric arc.

As the result of high-speed shooting of plasma torch, files recorded in the .avi format were captured. Each file was a sequence of separate frames formed by image sensor of Citius imaging camera. Thus, “avi” files reflect the dynamics of plasma radiation intensity of different plasma torch modes. Then the files were further processed: values of all pixels of each j -th frame are summed up, the total sum is recorded into j -th position. The result of summation was recorded into the j -th position of the new vector, the length of which corresponded to the number of frames in the “avi” file.

The study used a recording speed of 4000 frames/s with a resolution of 320×306.

As part of the research performed, a number of experiments with different air consumptions modes were conducted that are presented in the table. Air flow rate for each of the circuits varied from 0.9 g/s to 1.75 g/s and the plasma torch power varied up to 10 kV, the total duration of

experiment did not exceed 30 minutes and plasma torch showed stable operation during them. For all conducted experiments, the plasma torch power strength and arc voltage were synchronously measured with a time interval of 100 μ s.

Measurement of oscillogram of current instantaneous values (marked with blue) and arc

voltage (marked with red) for characteristic mode 13 are shown in fig. 2.

The calculated value of arc power as the product of the instantaneous values of current and voltage is shown in blue in Figure 3 and dependence of radiation intensity of the plasma when observed from the front video camera position – in red.

Table

Plasma torch operation mode

Record No.	Flow rate G_1 , [g/s]	Flow rate G_2 , [g/s]	Flow rate G_3 , [g/s]	Total flow rate G , [g/s]
Video camera is perpendicular to the main plasma torch axis (profile)				
1-3	0.9	1	1.75	3.65
4-6	0.9	0.84	1.75	3.49
7-9	0.9	0.74	1.75	3.39
10	0.9	0.61	1.75	3.26
Video camera is coaxial to the plasma torch main axis (frontal view)				
11	0.9	0.92	1.72	3.54
12	0.9	0.84	1.72	3.46
13	0.9	0.74	1.72	3.36

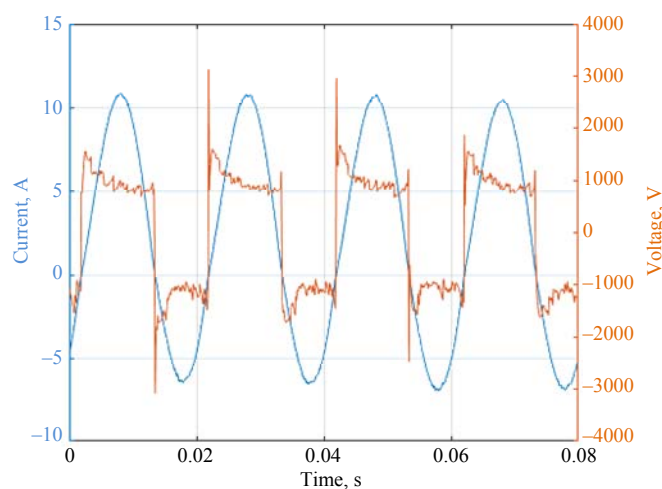


Fig. 2. Current and arc voltage oscillograms for mode 13

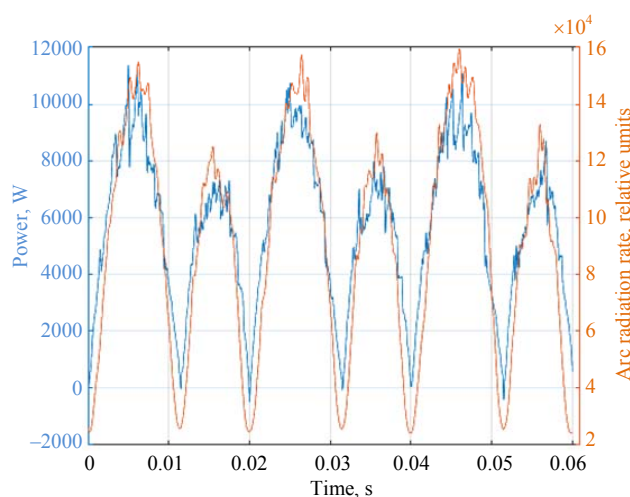


Fig. 3. The calculated value of arc power and the observed intensity of plasma radiation at frontal video camera position

Since the electrical parameters of the arc were calculated with a time interval of 100 microsec and the video frames were recorded with a time step of 250 microsec, the samples were unified using interpolation for the calculation of correlation coefficient of two dependencies shown in fig. 3. Correlation coefficient between the calculated arc power value and observed plasma radiation intensity was $R = 0.9612$, which confirms the assumption that the arc radiation intensity measured by high-speed video camera reflects the evolution of electric arc plasma energy in a good approximation.

For the calculated discharge power function (fig. 3) and plasma radiation intensity, the frequency characteristics of processes was determined using Fast Fourier Transformation (FFT).

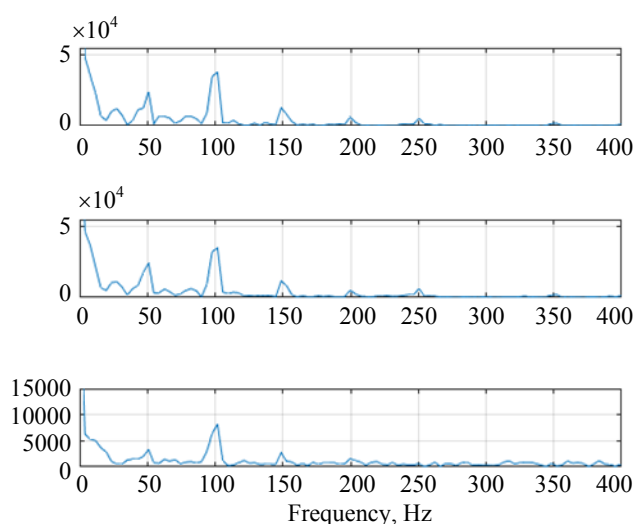


Fig. 4. Fourier Transformation: upper chart—fft of the calculated value of arc power; middle chart—fft of the plasma radiation intensity at frontal camera position (coaxial to the plasma torch main axis) and lower chart—fft of the plasma radiation intensity when the camera is perpendicular to the plasma jet at the plasma torch outlet

Fig. 4 shows the results of Fast Fourier Transformation for the calculated value of the arc power (upper chart) and plasma radiation intensity at two video camera positions – frontal

(middle chart) and profile (lower chart). For all transformations the main frequency was 100 Hz and a very close ratio in amplitude of satellite frequencies that were multiples of the main frequency.

Using invertibility property of Fourier transformation, it follows that the coincidence of the fundamental frequencies of the Fourier transformation of functions results in closeness in the first approximation of the functions themselves. Thus and with similar consideration it can be assumed the plasma radiation intensity correlates well with the electric arc discharge power.

Conclusion

The study investigated the processes of discharge development in plasma torch at two different positions of a high-speed camera and compared arc power calculated according to the current oscillograms and voltage with the observed intensity of plasma radiation. 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.

Comparison of the calculated value of the electric arc power and observed plasma radiation intensity confirms the assumption that the plasma radiation intensity measured using high-speed video camera shows the evolution of the electric arc plasma energy in good approximation, at the same time the correlation coefficient is ~ 0.9612 .

Additional confirmation of the possibility of using plasma radiation intensity for the analysis of plasma torch electric arc power is based on the invertibility property of Fourier transformation from which it follows that the coincidence of the fundamental frequencies of Fourier transformation results in closeness in the first approximation of the functions themselves.

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