Studying optical characteristics of an axial symmetric non stationary plasma

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Abstract. The distribution function of arc pulsations was obtained as functions of current intensity, gas flow rate, and distance from the cathode in a plasmatron with a fixed arc length. The intensities of plasma emission were measured by the method of transverse images. As the results, the temperature distribution over the arc radius was determined and the effect of pulsations on the measurement precision was noted.

1. Introduction
A significant divergence of the results on the temperature distribution in electric arc and microwave plasmas occurs by their spectroscopic studies often. Partially, it is connected to the fact that the common spectroscopic methods provide reliable results when the plasma properties are stable on time. If the plasma is non stationary, the distribution of the investigated quantity will be determined with a certain error, which depends on the degree of plasma instability and the kind of time averaging of the quantity.

The present work is aimed at experimental study of pulsations in axial symmetrical, low temperature plasma accounting for the effect of these pulsations on the temperature of plasma.

Apparatus and experimental procedures.
The plasmatron under experiment was composed of the sectioned interelectrode insert and the vortex gas stabilizer of arc. The arc chamber diameter was equal to $d = 1$ cm and the length of interelectrode insert was $a = 10$ cm. The plasmatron had included also the cathode and anode units, the interelectrode insert sections, the gas curling ring, insulating and sealing spacers, flanges, bolts, and nuts required to assembling the plasmatron. The anode and the interelectrode insert sections were manufactured of copper. A hafnium rod embedded into the copper holder was the cathode. The insert sections were insulated from each other by Teflon spacers and were cooled by water. A sections being the optical one had a rectangular slit with 1 cm of height and 0.1 cm of width. The slit was closed by K8 optical glass. This section makes it possible to observe the arc column in a particular channel cross section. By varying the optical section location, it makes possible to investigate the diver arc domains. The arc was formed between the cathode and the cylindrical anode. The air was fed tangentially into the arc chamber through the holes of the curling ring of the initial cross section. To provide laminar gas flow, the internal plasmatron channel surface was polished.

A NAC Memrecam GX8 high-speed camera was used to record the arc pulsations. The emission of selected arc cross section was projected on the camera objective. The camera provides made recording at a highest sensitivity (> 20000 ISO) with the minimal exposure time of 600 ns. During the experiment, the digital image of the arc position was registered in the camera’s memory to be afterward transferred for processing to a PC. Using specific image processing software, we was obtaining the registrogram of the arc pulsations in the plasmatron channel.
Results
We investigated the arc pulsations within a continuous current range of $I = 100 - 250$ A, the gas flow rate of 0.2 – 8 g/s, and the distance from the cathode $z = 1.8 - 8.7$ cm. It was detected that the arc undergoes low frequency (~300 Hz) pulsations as well as high frequency (~104 Hz) ones and complex physical processes take place in the arc chamber. We studied the high frequency arc pulsations at the current intensities $I = 100, 150, 200, 250$ A, the gas flow rates $G = 0.4 - 8$ g/s, and the distances from the cathode $z = 1.8 - 8.7$ cm.

It follows from the registrogram analysing at low gas flow rates that the pulsations are random and submit to the normal distribution law

$$
\Phi(x) = \frac{1}{\sigma_x \sqrt{2\pi}} e^{-x^2/2\sigma_x^2} \quad (1)
$$

The registrogram processing makes it possible to determine the standard deviations of the arc axis $\sigma_x$ depending on the current intensity, the gas flow rate, and the distance from the cathode. The analysis of the experimental results shows that the pulsation amplitude growth with the increase of $G$ and $z$ and with the decrease of $I$. The $\sigma_x$ values obtained here are in a good agreement with the results of [1]. Thus, we be able to constat that, at low rates of gas laminar flow, the arc pulsations may be described by the normal distribution law (1). The random pulsations of the arc are caused by several factors such as turbulence in the gas flow, the arc interaction with its own magnetic field and the channel wall, rotation of the preanode section of arc positive column, and the smallscale shunting of discharge [2]. At a flow rate of more than 2 g/s, shape of oscillations has another form (Figure 1).

It is seen from Fig. 1 that harmonic oscillations superimpose on random fluctuations. Distribution function of oscillations of the arc axis has been constructed with accordance to the records. This results in the axis of arc oscillates in the channel region of 2.5 mm and the most probable position of the arc is not placed on the axis of the channel, but at some distance from it and, in addition, with increasing the current intensity, the amplitude of oscillation increases. Taking into account these experiments one can propose the following model of an axial symmetric plasma arc: at low gas flow rates (up to 2 g/s), the arc begins to rotate as a whole (Fig. 2). The axis of the arc $O'$ moves along a circumference of radius $a$ in the plane $z = \text{const}$, the center of which is a subject of random fluctuations described by the formula (1). In this figure, the solid circumference curve represents the true size of the plasma, large dotted circumference – the observed size of the plasma and the small dotted circumference of radius $a$ - track of rotation of the plasma of radius $R$. By the letters HOY, the laboratory reference frame is denoted and by H'O'Y' – the coordinate system associated with the plasma.

The distribution function of harmonic oscillations is represented as:

$$
\varphi_2(x) = \frac{1}{\pi \sqrt{a^2 - x^2}}, \quad a \leq x \leq a, \quad \varphi_2 = 0, \quad a < |x| \quad (2)
$$

Consequently, the distribution function based on the random harmonic vibrations of $O'$ is equal to:
\[ \varphi(x) = \int_{-a}^{a} \frac{1}{\pi \sigma \sqrt{2\pi (a^2 - \xi^2)}} \exp\left[-\frac{(x-\xi)^2}{2\sigma^2}\right] d\xi. \]  

(3)

To determine the plasma temperature accounting for its spatial pulsations, it is necessary to obtain the time averaged distribution of the emission intensity \( I_v(x) \) over the height of the spectral line. Knowing the distribution function \( \varphi(x) \), the proper distribution \( q_v(x) \) can be determined by solving the Fredholm equation of the first kind

\[ I(x) = \int_{-R}^{R} q(x') \varphi(x - x') dx', \]  

(4)

where \( R \) is the plasma radius. Here, the distribution function \( \varphi(x-x') \) is described by the normal distribution law (1). The equation (4) has been solved by the Phillips-Toumi regularization method [12, 13]. We wrote the program in the C++ language. Figure 2 shows the results for the currents intensities 100 and 250 A, the gas flow rate 6 g/s, and \( z = 5.2 \) cm.

![Figure 2: Distributions of the \( I_v(x) \) and \( q_v(x) \) intensities at \( z = 5.2 \) cm, \( G = 6 \) g/s at \( I = 100 \) A (1;3) and 250 A (2;4).](image)

The \( I_v(x) \) distributions were spectroscopically determined according to the NI 493.5 nm line; the \( q_v(x) \) are found according to formula (4) by using of the experimental data on the \( I_v(x) \) and distribution function (3). It is seen that the pulsations cause underestimation of the intensity at the arc axis and its overestimation at the periphery. With the current intensity increasing, the line profile becomes tighter.

From the measured values of \( I_v(x) \) and \( q_v(x) \), we found the radial emissivities and the temperatures. Figure 3 shows the results. We can see the electric arc pulsations influence on the character of the temperature distribution over the radius. Neglecting the arc pulsations results in temperature underestimation at the axis zone and its overestimation at the periphery, as well as in the temperature profile distortion.
Figure 3. Temperature distributions over the arc radius at \( z = 5.2 \) cm, \( G = 6 \) g/s, \( I = 100 \) A (1;2) and 250 A (3;4).

References

[1] Zakirov I.M., Zalyalieva F.F., Timerkaeva D.B., and Tukhvatullin R.S., *High Temp.*, 2011, vol. 49, no. 3, p. 330.

[2] Dautov G.Yu., in *Modelirovanie i metody rascheta fiziko-khimicheskikh protsessov v izkotemperaturnoi plazme. Sbornik* (Simulation and Methods of the Calculation of Physical-Chemical Processes in Low-Temperature Plasma: A Collection of Papers), Moscow: Nauka, 1974, p. 185-208.