Investigation of temperature field of weakly ionized gas jet by the background oriented schlieren method

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Abstract. The paper shows the possibility of using the background oriented schlieren technique to study the temperature field of a weakly ionized plasma jet created as a result of a spark discharge in argon at atmospheric pressure. The design of the spark source, the experimental setup, the experimental method and the processing of experimental data are presented. The temperature field of weakly ionized plasma jet and the temperature distribution around it were obtained.

1. The object of study and the scheme of experimental setup

The object of research in this work is a stream of weakly ionized plasma that is formed during a spark discharge in argon at a pressure close to atmospheric. The study of this object is important in the development and design of medical therapeutic plasma torches, when it is important to know the temperature of the plasma torch. Sources of weakly ionized plasma are increasingly used for the treatment of material surfaces, the application of functional (wear-resistant, electrically conductive, heat-resistant, decorative) coatings (electrical alloying), and the ozone formation.

In modern plasma processes there may be no mechanical contact of the instrument with the workpiece, the effect on the object is carried out only by plasma.

Plasma technologies are increasingly used for surface treatment, plasma cutting, welding; high power plasma torches are used for particle processing, waste disposal, surface activation, repair and hardening of machine parts, tools, dies. To control these technological processes, it is also necessary to know the temperature field inside and around the plasma flows.

The system is a coaxial construction consisting of central and external electrodes. At the end of the outer cylinder it is possible to install nozzles of various configurations for change of the jet geometry and variation of its speed. In addition, in a wide range, it is possible to adjust the input pressure values.

It is possible to install a central electrode of various materials, change the distance between it and the end nozzle. A spark occurs in the gap between the tip of the central electrode and the end of the external electrode (nozzle). The impulse voltage has the form of consecutive trains, with amplitude of 4 kV, followed by a repetition period of 10 ms.
The geometry of the discharge region is such that heating, excitation and subsequent ionization of argon atoms occur inside the system, and only neutral and excited atoms that are a source of optical and ultraviolet radiation, enter the open space.

The block diagram of the spark source is presented in figure 1.

![Block diagram of the spark source](image)

**Figure 1.** Block scheme of the spark source of low-temperature plasma:
1 – reducer, flow meter and manometer, 2 – gas supply tube, 3 – external protective cylinder, 4 – central electrode, 5 – external electrode, 6 – outlet gas jet shape, 7 – digital oscilloscope, 8 – resistor for measuring the discharge current, 9 – high-voltage source, 10 – gas cylinder.

The waveform of voltage in discharge gap is presented at figure 2. As can be seen from the waveform, the jet formed by the source represents the periodically repeating pulse trains. The duration of the pulse train is 8 ms, it contains 340 individual pulses and each of them has the duration of 23 μs.

![Waveform of voltage between electrodes](image)

**Figure 2.** The waveform of voltage between electrodes.
The background oriented schlieren method was used for visualization of the temperature field of a jet of weakly ionized gas produced in a spark discharge. The experimental setup for determination of the temperature field is shown in figure 3. The aim of the study was to test the possibility of applying background oriented schlieren method for diagnostics of a plasma stream that changes in time and researching to analyze the dynamics of the flow, so an unstable, and a randomly changing flow was formed. One of the possible flows is presented in figure 4.

Figure 3. The scheme of the experimental setup for determination of the temperature field of a weakly ionized gas jet by the background oriented schlieren method:

1 – background screen, 2 – spark source of low-temperature plasma, 3 – jet at the exit of the spark source, 4 – optical bench, 5 – measuring thermocouple, 6 – high-speed digital video camera, 7 – control thermocouple, 8 – personal computer, 9 – high-voltage power supply.

For the recording of the jet 3 of a weakly ionized gas formed by the spark source 2 by the background oriented schlieren method, it is necessary to use the high-speed digital video camera 6, personal computer 8 that is used for storing and processing of images. The video camera is focused on the background screen 1. The spark source is fixed on the optical bench 5; to create a spark discharge, a high-voltage power source 9 of the NP-750-30 type is used. At shooting, a Fastec HiSpec-1 digital video camera was used. The lens Navitar CCTVLENS was used to create a clear image on the plane of matrix. This camera allows shooting of high-speed processes with different frame rates. The kit includes a set of interchangeable lenses, that allows choose the shooting conditions and ensure the best quality of shooting. The aperture of the lens when shooting as closed as possible, it is necessary to ensure the greatest possible depth of field.

The background screen consists of chaotic points of various diameters. Randomness of the points is necessary, since the displacements of points inside and outside the object under study are different. If the location of the points is ordered, then a situation may arise when it is impossible to see the displacement of the points inside the flow under study.

There are the photos of the structured screen used for the background oriented schlieren method: without plasma stream at figure 5 and with plasma stream at figure 6.
The optical axis of the high-speed camera is aligned with the geometrical axis of the plasma torch. Before shooting, the scaling coefficient of the torch image transfer to the plane of the matrix is determined. Next, the images of the object under study (plasma jet) are recorded with frequencies of 1000, 2000 and 3000 frames per second during 2-3 seconds. This time is sufficient to obtain the necessary array of experimental data. Shooting is done with a depth of brightness with a dynamic range of 8 bits. The video camera is focused on the axis of plasma flow under study.

Radiation occurs in a wide range of wavelengths. So various light filters were used at the recording. Each of them corresponds to one of the lines of the argon emission spectrum. The use of light filters makes it possible to isolate narrow regions of the plasma spectrum where there are no argon lines, as well as to avoid the exposure.

2. Determination of the temperature field of plasma jet by background oriented schlieren method and processing of experimental data

The background oriented schlieren method [1, 3] is used for visualization of the temperature field of a weakly ionized gas. The object of study (plasma torch) is located between the high-speed digital video camera and the background screen.

The essence of the background oriented schlieren method is as follows. The screen images of the object under study and without it are recorded using a high-speed digital video camera. The images are randomly structured black dots on a white background. One image is recorded in the absence of a disturbed medium in the image transmission channel. In another picture, the medium is perturbed by the plasma jet that leads to the change in the optical properties of the medium. In the presence of a disturbed medium (thermally excited gas), the position of the background screen points changes. This changes the structure of the image of the background screen.

Displaces of the object points are registered. With the help of cross-correlation processing, changes in the position of points on the structured screen image are analyzed. Further processing is reduced to a change in the coordinates of the background point on screen. It is associated with a change in the refraction of the medium that depends on temperature. Analyzing the obtained images, we can trace the dynamics of the plasma torch development. The field of correlation coefficients is investigated. Correlation equation [1] is

\[
B_{f_{k_1k_2},g_{k_1k_2}} \approx \frac{1}{n \cdot m} \sum_{k_1=1}^{n} \sum_{k_2=1}^{m} \left( f_{k_1k_2} - \mu_f \right) \left( g_{k_1k_2} - \mu_g \right),
\]

where \(B\) – value of correlation coefficients; \(n\) – number of rows; \(m\) – columns number of the image matrix; \(f_{k_1k_2}, g_{k_1k_2}\) – arbitrary random sequences of the values of the background screen point displacements; \(\mu_f, \mu_g\) – average values of these sequences, respectively.
Distribution of background screen points in the range of values of correlation coefficients from 0.3 to 1.0 rel. units is presented at Figure 7.

![Figure 7](image)

**Figure 7.** Distribution of background screen points in the range of values of correlation coefficients from 0.3 to 1.0 rel. units: 1 – spark source of low-temperature plasma, 2 – plasma flow under study, 3 – distribution of displacements of the background screen points.

For obtain of the temperature field, it is necessary to determine the normalization factor relating the values of the displacements of the background screen points and the temperature at the reference point. The temperature values are recorded using two thermocouples: a reference one (determining the temperature outside the object under study). The probe one is located in close proximity to the object under study.

Continuous recording of temperature is carried out using the ADC. A sequence of temperature values is formed at the studied point at successive times with steps of 0.1 s.

The algorithm for converting the field of displacements of the points of the background screen in the temperature field is as follows. On the original image there is a vertical or horizontal straight line. The temperature obviously varies evenly along it. Next is the sum of the density gradients along this line.

\[
S = \sum_{i=0}^{n-1} \text{Re}(AB_{i,j}),
\]

where \(AB\) – original complex matrix representing the vector field \(i, j\) – row and column numbers, respectively.

In Mathcad the recording of vectors into a matrix is performed in a complex form. The real part of matrix is equal to the horizontal component, and the imaginary part - to vertical component.

To sum up the gradients along a horizontal or vertical straight line, it is necessary to lay down separately the real and separately imaginary components of the matrix elements.

The density gradient is proportional to the gradient of the refractive index and the temperature gradient. Then the temperature difference at the end points of the line (boundary conditions) is divided by the sum of the gradients.
\[ x = \frac{T_2 - T_1}{S}, \quad (3) \]

where \( T_2 \) and \( T_1 \) – temperatures in °C at the opposite ends of the line.

Thus, we get the temperature difference per unit gradient. It is possible to calculate the temperature change from one point of the vector field to another.

After normalization, the temperature field is calculated vertically and horizontally. To do this, take the temperature at any edge of the image (boundary conditions). The temperature of entire field is calculated with the help of sequential addition.

\[ TH_{n+1,i,j} = TH_{n,i,j} + x \cdot AB_{n+1,i,j}, \quad (4) \]

where \( n \) – the number of rows of the matrix.

A similar procedure is performed in the perpendicular direction.

Then the field values are averaged at this point in the vertical and horizontal direction:

\[ T_{i,j} = \frac{TV_{i,j} + TH_{i,j}}{2}, \quad (5) \]

where \( TV \) and \( TH \) – two matrix of the temperature field calculated in the vertical and horizontal directions, respectively.

The resulting value is equal to the temperature of plasma stream at this point.

The temperature distribution inside and around the plasma flow are shown at figure 8.

![Figure 8. Temperature distribution inside and around the plasma flow: 1 – plasma flow under study, 2 – spark source of low-temperature plasma, 3 – temperature distribution, °C.](image)

The results show that the temperature of plasma jet under study is in the range from 19 to 25 °C. The obtained temperature values indicate that this source forms a stream of cold plasma. The thermodynamic temperature at the outlet of the cylindrical tube is close to room temperature (23 °C) or slightly lower. Since the temperature variation inside the plasma flow is insignificant, it can be concluded that at the exit from the discharge gap there are mainly excited atoms. According to the classical theory, the thermodynamic temperature is related to the density of electrons and atoms \((p = nkT)\). To analyze the composition of the particles at the exit from the discharge gap, an estimate of the density of excited atoms in the region under study was made.
It is established that the values of particle density both inside the plasma flow and around it have values of the same order \( n \approx 10^{26} \text{ I / m}^3 \). This fact indicates that at the exit from the discharge gap, excited atoms predominate, and the ionization process takes place inside a cylindrical tube, near the central electrode. Since the density of particles inside the outgoing plasma stream and outside it are practically not differ (the difference does not exceed one order of magnitude), it can be concluded that in this medium the electron density is small, and the field of study consists mainly of excited atoms.

The temperatures of the excited atoms in the outgoing plasma flow decrease slightly compared with the temperatures of the surrounding particles. This effect can be explained by the fact that the ionization of the flow created by this source occurs near the central electrode inside the cylindrical tube. At the exit of the tube, only excited particles can be observed. And their kinetic energy is less than the energy of the surrounding particles.

The obtained experimental data are consistent with the data of other authors [6–15]. The paper shows the possibility of using the background oriented schlieren method for the diagnostics of various plasma medium, including the medium with a high degree of ionization. The considered method allows obtain the temperature field of the plasma flows under study, as well as the concentration field of electrons and excited atoms.

In addition, the use of the background oriented schlieren method allows you to take pictures of various stages of the discharge, analyze the temperature and composition of particles both inside the plasma flow and around it. The method can also help in the analysis of particle drifts and the search for the causes of instabilities of high-temperature plasma, and hence in the search of methods for elimination of these instabilities.

The background oriented schlieren method for plasma streams also allows control the parameters of plasma medium (temperature, concentration, etc.). It can be widely used at various plasma technological processes, such as plasma spraying, plasma particle processing, plasma chemistry and etc.

It should be noted that this method is purely optical, i.e. it is contactless. It does not distort the parameters of the object. It allows exploration of the optical inhomogeneities of small length. The method is simple and universal.

3. Conclusions
In this paper the possibility of applying the background oriented schlieren method to determine the temperature field of a weakly ionized plasma jet is confirmed. A method for recalculating the field of displacements of background screen points in the presence of a plasma stream into the temperature field is presented. Using the background oriented schlieren method it is possible to analyze the temperature and composition of particles inside and around the plasma flow at different points in time. Sources of this type must be stabilized in order to obtain pulses of the same duration and amplitude to ensure accurate determination of the dose of exposure to biological tissue. As an object of study, a construction similar to medical sources of low-temperature plasma was used. At the work with such sources it is necessary to understand what particles are present in the jet of this source (neutral atoms, electrons, ions). For this aim the temperature field of this source jet should be determined. It is necessary to understand the value of UV radiation in this jet, and which of the listed factors is important in assessing the biological effects on human tissue.

In the future, it is intended to move from the temperature field to the density field of particles forming the plasma flow. The results show that in the studied jet charged particles are practically absent. There is intense ultraviolet radiation that is the main factor influencing biological objects. Thermal factor does not play a significant role. The field temperature is slightly different from the environment.
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