Spatial-temporal diagnostics of the system of a plasma stream interacting with a surface of heat resistant material

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Abstract. In an automated measuring complex using optical and spectral methods the spatial and temporal changes in the parameters and composition of nitrogen plasma jet were investigated. The plasma jet was flowing out of the nozzle of the plasma torch with 10–12 kK temperature and acting on the sample of MPG-6 graphite. Due to the heating of the sample to the temperatures of 2.5–3 kK the influence of the sublimating material of the sample on the plasma composition and temperature in the near-surface region of the sample was investigated. An original method based on the analysis of movement of optical inhomogeneities in the plasma flow was used to estimate the plasma jet velocity in the region where it interacts with the sample. The combined analysis of the results of two-positioning video recordings opens up the possibility of determining spatial-temporal distributions of the plasma jet velocities, in medium and high pressure environments, in the ranges from few to thousands of m/s and 3–15 kK temperatures.

1. Introduction

The researches of intensive destroying action of high-temperature reactive plasma flow upon a heat-shielding material are of current urgency and considerable interest for modern science and technology [1–5]. The complex and varied processes that accompany exposure of the heat-resistant materials to the plasma jet were intensively studied for half a century and predetermined major achievements in space exploration. Currently, work is continuing on the creation and study of new thermal protective materials based on composites (SiC–C, SiC, etc), detailed studies of their destruction mechanisms under the influence of high temperature and chemically active media are carried out [4–8].

The possibility to obtain homogeneous and heterogeneous gas flows with predetermined pressure and temperature in wide range of velocities, up to supersonic ones, makes generators of low-temperature plasma to be the unique tool for modeling interaction of the high-temperature flow with a surface of any material. With the interaction being transient, both interaction media being inhomogeneous, the plasma flow composition being varied because of material mass loss, the experimental research demands a complex of measuring tools so that to provide correct simultaneous determination of the constitutive properties and parameters of both media with necessary spatial and time resolution. In this work we present the experimental setup and methods that were designed and constructed by our team that allows for automated synchronized
recording of the spectral data from the investigated sample surface and the plasma in the near sample surface region, and the velocity of the plasma stream incident on the investigated sample. Since this work was dedicated to device the experimental setup and methods of investigation, MPG-6 graphite was used as a sample material since most of its thermodynamic properties are well investigated and recorded [9–12].

An experimental stand was designed and constructed, which includes: the generator of high-enthalpy ($H > 20$ kJ/g) argon, nitrogen and air plasma jet with a diameter of 8–20 mm and a calorimeter which measures the heat fluxes in the region where plasma stream interacts with investigated samples.

A plasma torch with arc vortex stabilization and an expanding channel of an output electrode is used as a plasma generator (figure 1), which provides high flow performance, efficient heating of the working medium and low thermal losses in a water-cooled surface of the anode. Extensive research and technological possibilities of this type of plasma torches are presented in review [13]. The schematic of the measuring complex is shown in figure 1. Plasma torch with an expanding output electrode (anode) 6 mm or 10 mm diameter creates a downstream plasma jet with a temperature at the anode-nozzle outlet 10–15 kK, defined by the working medium (argon, nitrogen, air) and the arc current which can vary in the range 100–400 A. Plasma jet enters into the ambient air at a velocity controlled by plasma forming gas flow rate and plasma density at the nozzle exit. Heat-resistant sample is placed at the plasma jet axis at a selected distance from the outlet section of the plasma torch; the bottom flat surface of the cylindrical sample is fixated on the uncooled 2 mm diameter tungsten rods.

Automated control unit synchronizes the operation of measuring systems and generates control signals transmitted to the auxiliary devices. These programmable signals transmit the programs for the: stepper motors that ensure the movement of the spectrometers optical fibers across the plasma jet for Avaspec 3648 and along it for Avaspec 2048, introduce and remove interference filters in front of high-speed cameras Phantom, Motion Pro and VS-FAST, and the programmable input–output of the graphite rod carried out by an electromagnetic drive. The graphite rod is the source of “markers” for the analysis of plasma velocity in the jet.

2. Characteristics of nitrogen plasma in the jet and in the zone of interaction with the sample

Spectral AvaSpec systems for longitudinal and transverse scanning of the plasma jet emission enable continuous monitoring of the emission spectra with a spatial resolution of 0.5 mm throughout the tests. Example of emission spectra from the paraxial region of the nitrogen plasma jet registered on the Avaspec 2048 device is presented in figure 2.

Processing of acquired spectra revealed a change in the character of the axial plasma electron temperature values along the jet for different arc currents.

The three-channel fiber-optic spectrometer AvaSpec 2048 (spectral range 220–950 nm) with a spectral resolution of 0.2–0.5 nm detects the plasma radiation along the longitudinal coordinates of the downstream plasma jet incident on the sample surface. Monitoring of spatial-temporal changes of plasma emission spectra is performed by scanning of the plasma jet sharp image formed by lenses using spectrometer fiber optic light guides. The detailed picture of changes in the near-surface region of the plasma is recorded with a scale of 1 : 1 on the high-speed camera and MS 5204i spectrometer with an Andor matrix camera at the spectrometer outlet. The Andor camera records plasma spectral intensity distribution along the vertical $z$ axis near the sample surface (0–5 mm above the sample surface) and thermal radiation of the heated sample in the selected spectral range, the width of this range is determined by the dispersion of the spectrometer and the length of the matrix. The dimensions of the matrix are $1048 \times 256$ pixels with a pixel size being $26 \times 26 \mu m^2$. Thus, with this setup it is possible to simultaneously record the spectra over about 6 mm of the interaction zone.
Figure 1. The measuring complex scheme: 1—plasma torch; 2—plasma stream; 3—sample under investigation; 4—automated control unit; 5—high-speed camera Phantom Miro M110; 6—high-speed camera Motion Pro X3; 7—high-speed camera VS-FAST; 8—spectrometer MS5204i; 9—Andor matrix camera; 10—spectrometer Avaspec 3648; 11—spectrometer Avaspec 2048; 12—focusing lenses; 13—graphite rod; 14—electromagnetic drive; 15—stepper motors; 16—interference filters.

The recorded spectra present the radiation from the sample surface, the near-surface plasma boundary layer and from the oncoming plasma jet, as shown in figure 3.

Such changes of molecular spectra near the sample surface are also observed when this zone is scanned by Avaspec 2048 spectrometer. Figure 4 presents the emission spectra of the plasma at the sample surface and at 1–4 mm distance from the sample. It is clear how the radiation intensity of CN radical rapidly increases near the sample surface.

Using standard molecular spectra modeling programs the vibrational and rotational temperatures of the emitting molecules N\(_2\), N\(_2^+\), CN were estimated, in the near-surface region of the oncoming plasma stream.

Figure 5 shows spectra registered by Andor camera obtained for distances up to 2 mm from the sample surface. For the convenience of comparison of the intensity of molecular bands the continuous part of the spectrum was subtracted from all of the spectrograms.

As can be seen from figure 5, when approaching the sample surface there is a significant increase in the emission intensity of cyanogens (CN) radical molecular bands. As shown by a comparison of the experimental spectrum with the model, vibrational and rotational temperature of cyanogen drop when approaching the surface of the sample and the relative concentration of cyanogen increases rapidly as shown in table 1, where \( h \) is the distance from the top surface of the investigated sample, \( T_v \) is vibrational temperature, \( T_r \) is rotational temperature, \([\text{CN}] : [\text{N}_2^+]\) is the ratio of concentrations of CN molecules to N\(_2^+\) molecules. The increase in the concentration...
of cyanogen is probably due to the nitrization of the carbon that is released into a high-enthalpy nitrogen plasma stream during the destruction of carbon sample in the process $C + N \to CN$, this process commences at high temperatures in both the gaseous environment around the sample and on the sample surface [1].

Registration of molecular spectra near the surface of the sample was also performed independently by Avaspec 2048 spectrometer, which was scanning spectra along the axis of the plasma jet. Figure 6 shows the spectra at different distances from the target surface in the same range of wavelengths as was recorded by Andor camera. For the convenience of comparison the continuous spectrum was also subtracted from all the spectra. A comparison of the experimental
Figure 4. Emission spectra of nitrogen plasma jet near the surface of the graphite sample; the low-wavelength spectrometer channel.

Table 1. Data from the Andor matrix camera.

| h (mm) | $T_v$ (K) | $T_r$ (K) | [CN] : [N$_2^+$] |
|--------|----------|----------|-------------------|
| 2      | 7800     | 5500     | 0.80 : 0.20       |
| 1      | 7500     | 5000     | 0.87 : 0.13       |
| 0      | 7000     | 5000     | 0.95 : 0.05       |

spectrum with the model allowed determining the rotational and vibrational temperatures of cyanogen and its relative concentration in this case as well. Figure 7 is an example of such a comparison. It may be concluded that in the given wavelength range the experimental spectrum agrees well with the model.

Rotational and vibrational temperatures and the relative concentration of cyanogen and N$_2^+$, calculated on the basis of Avaspec 2048 readings are presented in table 2.

In general both measurements give a similar picture of changes in the vibrational and rotational temperatures in the near-surface region of the plasma, and the ratio of the unperturbed plasma components and the products of its interaction with the material from the surface of the sample. This apparently indicates the decisive role of the process C + N $\rightarrow$ CN in the chemical destruction of the graphite when it is exposed to high-enthalpy nitrogen plasma jet.
Figure 5. Comparison of the Andor spectra at different distances from the target surface; the wavelength range 375.6–394.0 nm.

Table 2. Data from the Avaspec 2048 spectrometer.

| $h$ (mm) | $T_v$ (K) | $T_r$ (K) | $[\text{CN}]: [\text{N}_2^+]$ |
|---------|-----------|-----------|-----------------------------|
| 2       | 7000      | 6000      | 0.73 : 0.27                 |
| 1       | 7000      | 5000      | 0.88 : 0.12                 |
| 0       | 6100      | 5000      | 0.95 : 0.05                 |

3. Movement of optical inhomogeneities and the speed of the plasma jet

Nowadays remote methods for the speed measurements are used which do not affect the dynamic characteristics of the stream. One such method is the introduction of small-scale inhomogeneity into the stream and analysis of its movement by optical methods. These include in particular the method of registration of velocity fields by the images of micro particles introduced into a stream and illuminated by a laser (particle image velocimetry—PIV) [14]. The velocity measurements of this method are based on the determining the displacement of the particles within a specific time interval. Advantages of this method for velocity determination consist of that it is a non-
contact method; it allows obtaining the instantaneous velocity distribution and has no significant disturbing influence on the stream.

Movement of the plasma jets during transient operation flow is accompanied by a large-scale turbulence, caused by twisting of the plasma flow needed to increase the resource life time of the cathode and the anode, the disruption of the boundary layer at the exit of the divergent nozzle of the plasma torch, the features of the current flow in the plasma jet and its binding to the electrodes, the roughness of the walls of the anode vortex channel, etc. When the plasma jet is registered by the video camera with high frequency $v \geq 1 \times 10^4$ Hz and low exposure time $\tau_e \leq 20$ $\mu$s, the “instant” structure of the turbulent flow can be obtained, with a typical size of turbulent moles of 5–10 mm, which is comparable to the radius of the jet. Therefore, in such flows the velocity measuring method could consist of measuring the velocity of plasma emission optical inhomogeneities that are caused by the turbulization of the jet. The disadvantage of such speed measurement of the selected characteristic (shape, color) portion of the turbulent jet is the absence of a binding of the selected longitudinal coordinate velocity values to the transverse coordinate $r$, since when registering the images across the stream the illumination along the chord is integrated. The introduction of optical inhomogeneity in the center plane allows making this binding.

**Figure 6.** Comparison spectra recorded by Avaspec 2048 at different distances from the target surface; the wavelength range 373.7–396.7 nm.
Figure 7. Example of the comparison between the registered spectrum by Avaspec 2048 and the computational model; the wavelength range 363.5–405.5 nm.

The proposed method of introducing a localized inhomogeneities in the plasma stream consists of placing in the desired longitudinal coordinate along the diameter of plasma jet a source of plasma clumps, micro- and nanoparticles, that will move in the plasma stream without slipping and that will have a different luminous intensity when compared to the surrounding environment. The transverse size (diameter $d$) of the introduced material should not cause hydrodynamic perturbations of the jet ($d \ll D_{pl}$), and its thermal stability should provide it with enough life time for conducting plasma velocity measurements. At $U = 100–200 \text{ m/s}$ this would be the time necessary to make a few (2–3) thousands of video images, i.e. $\tau_m = N/v = 3 \times 10^9/10^4 = 0.3 \text{ s}$.

Schematic of the setup for the measuring the local speed values of the moving plasma stream is shown in figure 8. The plasma stream that is generated by the plasma torch is incident on the rod that is placed across the centre of the plasma stream. Sublimate from the surface of the rod is carried down by the plasma stream and forms long-lived glowing plasma clumps, which move along with the stream. Optical inhomogeneities are recorded with one or two high-speed cameras, which with the necessary field depth, in the scale of 1 : 5 and spatial resolution of 30–59 $\mu$m perform frame by frame video recording of the extended paraxial region $\Delta z > D$ of the stream with a frequency of $(0.5–10) \times 10^4$ frames/s and selected exposure time $\tau_{\text{exp}} = 2–50 \mu$s, which is determined by the luminosity of inhomogeneities and their velocity.
Figure 8. Schematic of the setup for video recordings of the optical inhomogeneities motion: 1—plasma torch; 2—plasma stream; 3—graphite rod; 4—system for input–output of the rod; 5—plasma clumps; 6, 7—video cameras.

Inhomogeneities in luminosity in this case are due to the emerging “cloud” of ablating and sublimating carbon. As the preliminary experiments have shown there is also another type of optical irregularities observed by high-speed video cameras, which are the numerous tracks of graphite particles demolished from the graphite rod by plasma stream. They differ in size (from a fraction of a micron to hundreds of microns) and speed due to slip effect, these particles can substantially expand the experimental basis for the statistical analysis of the movement of optical inhomogeneities in order to determine the local velocities of the plasma stream.

Informativity of high speed video recordings of optical inhomogeneities that result from the graphite rod entry into the plasma stream is illustrated in figure 9. It presents the sequence of eight frames from the high-speed video camera depicting the entry of the graphite rod with a diameter of $d_0 = 2 \text{ mm}$ into a free-flowing air plasma jet with a diameter of $D = 60 \text{ mm}$. As a result of the thermal influence of the plasma stream with a temperature 7–8 kK on the graphite rod the sublimate is formed that as it moves away from the rod forms fragments (clumps 2 and 3 in figure 9) that are characterized by a bright luminescence, compact form and its weak change over time that allows to track the geometric centre of the clump. The velocity of these clumps geometric centers was determined by the scale of their displacement $\Delta z$ from frame to frame, and the time length between adjacent video frames $\tau = 1/\nu$, where $\nu$—the frame rate.

Clump 2 in figure 9 moves with a slight acceleration and reaches the velocity of $V_2 = 55 \text{ m/s}$; clump 3 moves with almost no acceleration and has velocity of $V_3 = 36 \text{ m/s}$. 
Figure 9. Video recording of optical inhomogeneities caused by ablation of a graphite rod. The frame rate of 5000 s$^{-1}$, 50 ms exposure time. Here, 1—graphite rod; 2, 3—plasma clumps.
Figure 10. Speed of optical inhomogeneities in nitrogen plasma stream (blue crosses) with and (red crosses) without the graphite rod; gas flow rate 1.5 g/s; $z$ is the distance from the plasma torches nozzle outlet.

Figure 11. Plasma spectrum without the graphite rod.
Figure 12. Plasma spectrum when the graphite rod is introduced.

Such trajectory analysis can be performed by computing software, especially taking into account the movement of thousands of registered optical inhomogeneities.

Values of local flow rates with minimal error with using this method can be obtained under the following conditions:

(i) Clumps from plasma-chemical rod materials are moving in the plasma stream without slipping relative to the surrounding gas environment;

(ii) The perturbing effect of the rod on the plasma stream is low and (or) not extent.

To test the effectiveness of this method a quantitative analysis was carried out on the results of high-speed video recording of optical inhomogeneities in the nitrogen plasma jet with a diameter of about 20 mm without the marker rod and with graphite, copper, and tungsten rods with their diameters varying in 0.7–1.0 mm range. The results of determining the movement speed of optical inhomogeneities in the nitrogen plasma jet (200 A current arc torch, the gas flow rate of 1.5 g/s, the diameter of the outlet nozzle 10 mm) observed at 20–70 mm distances from the nozzle exit (see figure 8), are presented in figure 10. The spread of vertical velocity values is apparently related to the fluctuations in the plasma jet and the dependence of the velocity on the radial coordinate at the point where the measurements were taken, which can range in $r/R = -0.8 \leftrightarrow +0.8$. The aggregate value of the velocity of the plasma “own” inhomogeneities and the velocity of inhomogeneities introduced by the rod that was placed at $z = 20$ mm in the
zone $z \geq 30$ mm have similar values and show a reduction in the speed of the plasma jet as it propagates downstream from 160 m/s at $z = 30$ mm to 100 m/s at $z = 70$ mm.

To analyze the perturbing influence of the graphite sublimate on the temperature and speed of the plasma jet a registration of the plasma emission spectra was performed at 1–2 mm downstream from the rod. The resulting spectra are shown in figures 11 and 12. The introduction of the rod substantially increases the intensity of CN bands, and carbon C I lines appear. Using the intensity of N I spectral lines that appear in both spectra and molecular bands the electron temperature and vibrational and rotational temperatures of the molecules can be estimated. For example, from analyzing spectra that are presented in figures 11 and 12, the use of $N_2$, $N_2^+$, CN bands leads to the values $T_v \approx T_r \approx 8$ kK.

4. Conclusion
As a result of spectral analysis the quantitative data was obtained on the effect of the graphite destruction products on the component composition of the nitrogen plasma, caused by the heating of the sample to the temperatures of 2.5–3 kK.

The first results of the use of optical inhomogeneities introduced into the stream by graphite rods for measuring the speed of the plasma jet show the suitability of the proposed method and merit further development.

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