Temperature field in the interaction region of high-enthalpy plasma stream and graphite surface

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Abstract. Study of heat and mass transfer process in the interaction zone between subsonic plasma jet and surface of sublimating heat-resistant sample is one of current interest topics of contemporary thermophysics and physics of heterogeneous plasma. Despite a large number of works being performed in recent years, many fundamental problems have yet to get an adequate solution or even to be tackled yet. The challenge of determining plasma parameters in the boundary region of plasma jet wrapping around the solid surface is one of these problems. This work presents first results of experimental determination of electron, atomic and molecular plasma component temperature fields in the deceleration area of the plasma jet hitting the surface of sublimating heat-resistant sample. One of the important aspects of this work is selection and rational of spectral diagnostics methods with high spatial and temporal resolution based on analysis of nonequilibrium atomic-molecular plasma kinetics.

1. Introduction
The boundary layer problem is one of the most important problems in the plasma dynamics. Significant progress in theoretical studies and mathematical modeling of sub- and supersonic devices is rarely reinforced by experimental results. When considered from the thermal property investigation point of view, plasma medium has an advantage over gas medium having a very information-rich emission spectrum. However, difficulties caused by spatial heterogeneity, nonstationarity, small dimensions of the boundary region and large parameter gradients often become blocking issues for the investigators. For example, work [1] presents the results for boundary layer study of two heat-resistant materials, asbestextolite and fiberglass, interacting with a subsonic plasma jet in an inductor plasmatrone. While this study was professionally performed utilizing the methods of quantitative spectroscopy, spatial and temporal resolution was rather low and the level of heat load (0.2–0.4 kW/cm²) was lower than the levels used in tests of heat-resistant materials [2]. In the basis of the determination of the plasma parameters from its radiative characteristics, the formulas of equilibrium thermodynamics were put in [1], which in the context of the problem in question need to be justified.

In order to illustrate the considerable lagging of experimental studies of boundary region for plasma jet wrapping around the solid surface we will point out that among works of the three latest Conferences on Magneto-Plasma Aerodynamics only a few works on spatial and temporal spectral diagnostics of nonequilibrium plasma have been presented [3]. Considerable advances in theoretical descriptions and mathematical modeling of interaction between plasma jets and materials [4, 5] need to be reinforced with quantitative experiments.
Figure 1. Observation geometry: 1—plasmatrone nozzle; 2—plasma jet; 3—sample; 4—lens; 5—observation system.

2. Plasmatrone selection
In order to create plasma with the required characteristics low-temperature plasma generators with vortex arc stabilization and expanding channel of plasma output electrode were used [6–8]. Plasmatrones of this construction prove high flow characteristics and plasmatrone lifetime, effective heating of plasma gas and low heat losses to the water-cooled parts allowing to obtain plasma of various gases (argon, nitrogen, air) by installing appropriate electrodes. The design with an expanding channel of output electrode was elected because it provides laminar jet flow for considerably high gas speed at its input. The advantages listed above make it possible to run this plasmatrone effectively in a wide range of operation parameters.

This plasmatrone allows us to obtain a slightly divergent \((2\alpha = 12^\circ)\) plasma jet of various gases (argon, nitrogen, air) with diameter \(D = 5–12\) mm, enthalpy 5–50 kJ/g and mean mass temperature 5–20 kK, full electric power of the arc discharge 5–50 kW and plasma gas flow rate 1–3 g/s.

In order to determine specific heat fluxes of plasma we performed calorimetric measurements for various values of electric current, gas flow rate and distance from the plasmatrone nozzle by using a water-cooled multisection copper calorimeter. The specific heat flux range at the distance from plasmatrone nozzle 10–30 mm was 0.02–1 kW/cm\(^2\) at plasmatrone power 5–10 kW for argon and 0.1–10 kW/cm\(^2\) at plasmatrone power 20–50 kW for nitrogen and air.

3. Geometry of the observed interaction region
Optical data acquisition scheme for plasma jet speed reduction zone on the sample should be designed in a way to reduce the registration difficulties caused by the features of the studied object (figure 1). First of all, such difficulties are spatial extent and inhomogeneity of plasma. The cylindrical or slightly divergent plasma jet created by plasmatrone with diameter \(d_0 \approx d < D\) wraps around the sample (where \(d_0\) is the plasmatrone diameter, \(d\) is a jet diameter, \(D\) is the
characteristic size of the sample). The optical length of the integration region of the radiation $L$ changes from $d$ to approximately $D$. Radiation intensity of CN radical, which is main product of graphite destruction, is at maximum power in the plasma jet speed reduction region caused by sample material being carried away and nitrified [9]. Another consequence of sample mass loss is the appearance of the crater on its surface facing the oncoming plasma jet. This way, optical observations of the interaction region are being complicated by two causes:

- Observed radiation comes from a path of variable length and composition.
- Crater formation causes a section of boundary region to be covered by sample from observing cameras.

These problems can be resolved in the following ways:

- Mean heat flux value $q$ is selected so that crater depth $\Delta$ does not exceed 0.5 mm within experiment time (60–100 s). It was found that it should not exceed 1 kW/cm$^2$.
- Interaction zone is observed at low angle $\alpha \approx \Delta_{\text{max}}/r_0$ where $r_0$ is crater radius.

4. Data acquisition system

We have designed and built an automated data acquisition complex for performing experiments on interaction between plasma jets and heat-resistant materials. Its components are shown in figure 2. It includes the following measurement tools.

The synchronized video recording system consists of the high-speed cameras Motion Pro X3 and VS-FAST and the super-high-speed Phantom camera. Combined with long-focus lenses and a system of extension rings, the cameras are able to register the region of interaction between
plasma jet and sample for the whole observation period (60–200 s) acquiring up to 15000 frames (30 Gb of data) to be stored in intermediate memory and be transferred to a personal computer later. These cameras also can be used as high-speed micropyrometers by inserting interference filters with bandwidth of $\delta \lambda_{1/2} = 10–12$ nm at given intervals.

The magnitudes of local values of brightness temperature in a given zone with diameter of 1.5–2 mm were measured by acquiring thermograms with a high-speed three-wavelength micropyrometer FMP1001 developed at the JIHT RAS. This device has temperature range of 1200–5000 K.

Spectral measurements are performed with three-channel and one-channel optical fiber spectrometers AvaSpec 2048 and AvaSpec 3648. The former has wavelength range 220–1000 nm, resolution 0.2–0.5 nm and is used to monitor radial distributions of plasma emission. The spectra obtained at the rate of 2–4 snapshots per second allow us to observe temporal evolution of processes in the interaction zone above the sample surface $\Delta Z \approx 1–5$ mm. The latter has wavelength range 220–1100 nm, resolution 1 nm and is used to register plasma emission along the jet axis. The optical fiber inputs of spectrometers are continuously moved horizontally and vertically respectively scanning the image of the plasma jet and sample formed by condensers 11, 12, 16 (see figure 2).

In order to ensure high spatial resolution of registered radiative characteristics of plasma, local parameters in the boundary region are monitored by MS-257 spectrometer. It utilizes an Andor CCD (charge-coupled device) matrix at its output (pos. 15 in figure 2) and has spectral resolution of 0.05 nm. This system takes 2D snapshots (X-axis—wavelength, Y-axis—spatial coordinates) of emission spectra of plasma and sample at given intervals at a set wavelength range containing spectral lines of ArI, NI, CuI to determine electron temperature [10], H$\beta$ line to determine electron concentration and CN, CO spectral bands to find vibrational and rotational temperatures.

Experimental estimation of the sample mass loss rate is achieved by sample weighting, two-position high-speed imaging and laser profilometry [11]. Two-position visualization was performed with Phantom and VS-FAST high-speed cameras at 30–50 FPS and 20–100 ms exposition at 1 : 5 scale. The cameras were installed so that their lines of sight were mutually perpendicular and could be used to record the whole duration of the experiment of 60–200 s. This allows us to get precise data on changes in sample volume and, sublimation rate from density and sublimating surface area.

5. Results
Space–time distributions of radiation intensity were obtained on our experimental setup (see figure 2) for plasma jet components (NI, N$_2$, N$_2^+$) and products of plasma–sample interaction (CI, CN*) (figure 3). They were used to determine time-resolved temperature of plasma electrons (figure 4) and vibrational and rotational temperatures of CN, N$_2$ and N$_2^+$ components in the interaction zone for the duration of the experiment, in the local thermodynamic equilibrium approximation, which is valid under the experimental conditions.

For the first time, the spectroscopy methods with high spatial (50 µm) and temporal (1 ms) resolution have been successfully utilized to determine variations in emitting carbon atoms (spectral line CI 247.9 nm) (figure 5) and radical (CN, transition $B^2\Sigma^+ - X^2\Sigma^+$) (figure 6) concentrations near the sample surface during its interaction with argon and nitrogen plasma jet. The obtained data shows that variations of CI and CN concentrations denote dynamics of sample material (mainly atomic carbon) admission into plasma and its plasmochemical transformations with atomic and molecular nitrogen.

For the first time 2D spectra have been obtained showing radiation intensity variation by wavelength and geometry coordinates for CN radical with low excitation energy (figure 7) in close proximity to the surface of graphite samples which allows to analyze temperature variation
Figure 3. Emission spectra of nitrogen plasma jet at various distances from sample surface on the 60-th second of heating at arc current 150 A.

Figure 4. Spatial and temporal variations of electron temperature in nitrogen plasma jet at various distances from sample surface at arc current 150 A.

patterns in the boundary region. The data on spatial distributions of CN are in quantitative agreement with the data from paragraph 2.
Figure 5. Space–time variations of CI 247.9 nm spectral line intensity with argon plasma and arc current 300 A.

Figure 6. Space–time variations for CN violet spectral band (transition 0–0, 388.3 nm) intensity with nitrogen plasma and arc current 300 A.

Figures 8 and 9 show the vibrational and rotational temperatures determined by numerical modeling of CN radical and N$_2^+$ molecular ion emission spectra for wavelength range 380–400 nm.
Figure 7. 2D spectra of nitrogen and argon plasma hitting the graphite sample. Coordinate 0 is the sample surface.

Figure 8. Observed and simulated spectra of CN radical and N$_2^+$ molecular ion at 0.5 mm from the surface.

Matching model values with observed ones at different distances from the sample surface allowed us to determine the ratio of their mole fractions at given coordinates.
Figure 9. Observed and simulated spectra of CN radical and $N_2^+$ molecular ion at 1 (a) and 2 mm (b) from the surface.

6. Conclusions
Analysis of relative populations of NI excited states in nitrogen plasma near sample surface allowed to determine spatial and temporal variation patterns of incident plasma jet electrons. A method for determining instantaneous temperature profiles of nitrogen plasma jet during its interaction with a heat-resistant carbon-containing barrier is proposed. We have shown that experimentally determined distributions of CN$^*$ radical concentrations in the interaction zone
can be used to gauge the efficiency of carbon nitrification process on the sample surface and in the incident plasma jet. Analysis of CN* distributions in time and space can help solve three problems together:

- Determining plasma parameters at minimum distance from the sample surface where atomic spectral lines are not present. This is possible due to excitation energy of B$^2 \Sigma^+$ state being as low as 3.07 eV.
- The vibrational-rotational structure of CN* spectrum provides a unique opportunity to determine both temperature characteristics of the nonisothermal plasma investigated in this work: vibrational and rotational temperatures, which are close under the studied conditions to the temperature of electrons and heavy particles temperature respectively.
- CN* radiation intensity is dependent on its concentration in plasma and thus can be used as an indicator of graphite sample mass loss rate since CN is the main end product of its destruction reactions.

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