Research methods of plasma stream interaction with heat-resistant materials

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Abstract. An experimental automated system was designed and constructed for studying the parameters and characteristics of non-stationary interacting system high-enthalpy-plasma stream–investigated sample: enthalpy of plasma in the incident stream; speed and temperature of plasma stream; temperature of electrons and heavy particles, ionic composition and their spatial distribution; heat flux incident on the sample (kW/cm²); surface temperature of the sample; ablation of the sample material, and others. Measurements of achievable plasma heat flux levels are carried out by calorimetry of plasma streams incident on the surface of multi-section copper calorimeter. Determination of acceleration characteristics for profiled plasma torch nozzle, as well as the gas flow rate is produced by measuring the total pressure using the Pitot tube. Video visualization of interacting system is carried out using synchronized high-speed cameras. Micropyrometry of the selected zone on the sample surface is carried out by high-speed, three-wavelength pyrometer. To measure the rate of mass loss of the sample, in addition to the weighing method of evaluation the methods of laser knife and two-position stereoscopy are used. Plasma and sample emission characteristics are performed with two separate spectrometers.

Research of thermal protection material sublimation in a reactive medium with strongly non-monotonic transport properties are highly relevant and have great interest in modern science and technology [1–3]. Of particular interest are the study of parameters and characteristics of non-stationary interacting system high-enthalpy-plasma stream–investigated sample: enthalpy of plasma in the incident stream; speed and temperature of plasma stream; temperature of electrons and heavy particles, ionic composition and their spatial distribution; heat flux incident on the sample; surface temperature of the sample; ablation of the sample material [4, 5], and other. To carry out such broad class of measurements an experimental automated system was designed and constructed (figure 1), which allowed studying the dynamics of interactions and alterations in the system incident-plasma stream–investigated sample. The system included calorimetry, high-speed synchronized video visualization, micropyrometry, laser profilometry and spectroscopy of plasma and sample emission characteristics. To adjust the equipment and test the methods of measurements preliminary study of the destruction of the isotropic graphite MPG-6 [6] (23 × 23 × 16 mm³) by non-reactive argon plasma was carried out.

As a source of high enthalpy plasma stream a generator of low-temperature plasma (GLP) with expanding channel of an output electrode is used [7], which produces weakly divergent
Figure 1. Synchronized measurement system: 1—plasma torch, 2—high-speed micropyrometer, 3—investigated sample, 4—cylindrical lens 5—telescope, 6—repetitive pulsed laser, 7—filter, 8—MS-257-Andor, 9—black and white high-speed camera VS-Fast, 10—particle tracks, 11—the boundary layer, 12—3-channel spectrometer AvaSpec 3648, 13—the single-channel spectrometer AvaSpec 2048, 14—Video camera Motion Pro, 15—neutral filter, 16—interference filter, 17—synchronization system (controlled pulses generator).

$(2\alpha = 12^\circ)$ plasma stream from different gasses (argon, nitrogen, air) with diameter of $D=6–20$ mm, enthalpy of 5–50 kJ/g and average weight temperature of 5–10 kK at full electric power of an arc discharge being 5–50 kW, and the plasma gas flow rate of 1–3 g/s. Measurements of achievable plasma heat flux levels are carried out by calorimetry of plasma streams incident on the surface of multi-section copper calorimeter. The measurements were carried out for different values of current strength, distance from the plasma torches nozzle and the gas flow rate. Determination of acceleration characteristics for profiled plasma torch nozzle, as well as the gas flow rate is produced by measuring the total pressure using the Pitot tube. Pitot tube is a curved capillary tube enclosed in a copper shell which is cooled by flowing water [8]. These measurements show that in argon plasma depending on the initial conditions, at the distance of 0–30 mm from the nozzle outlet the near axis speed changes in the range of 1000–300 m/s.
Figure 2. The luminescence of the sample with laser illumination and transformation in the field of temperatures (arc current of 200 A, 1 ms video exposure): (on left-hand side) no filter; (in the middle) with a 525 nm filter; (on right-hand side) the temperature field.

Video visualization of interacting system is carried out using synchronized high-speed cameras with three-color matrix Motion Pro X3 and VS-Fast. Micropyrometry of the selected zone on the sample surface is carried out by high-speed, three-wavelength pyrometer FMP1001 [9]. To measure the rate of mass loss of the sample, in addition to the weighing method of evaluation the methods of laser knife and two-position stereoscopy are used.

Pulsed laser LCM-DTL-319QT with focusing system (telescope and cylindrical lens) forms laser knife in the region of the sample surface with the width of 1 mm and length of 20–25 mm. With the use of two-position stereoscopy by synchronized cameras Motion Pro and VS-fast the change in the boundaries of the sample is determined and ultimately the change in volume is calculated. At the same time the third camera Phantom working in the 10 fps mode with 1 ms exposure records the laser knife trace on the surface of the sample, the software analysis of the change in the laser knife trace allows to determine the rate of sample sublimation in its crater. At the same time to determine the temperature in the crater and at the rest of the samples surface interference filters with allowed bandwidth of 590 nm and 525 nm (bandwidth width $\delta \lambda_{1/2} = 10$ nm) are introduced in the cameras light path. The 525nm filter is also used to record the trace of laser knife. Figure 2 shows an example of high-speed imaging of the plasma-sample interaction with laser knife trace present.

Spectral measurements are performed with three-channel and one-channel fiber optic spectrometers Avaspec 3648 and Avaspec 2048. Single-channeled fiber optic spectrometer Avaspec 2048 with a spectral resolution of 1 nm monitors plasma emission from the surface of the sample in the spectral range of 240–1000 nm. These measurements provide the diagnostics (with the frequency range of 2-4 spectra/s) of the changes in plasma chemical composition and plasma parameters in the region of its interaction with the sample ($\Delta Z \approx 2$–3 mm above the sample surface). Three-channeled fiber optic spectrometer Avaspec 3648 with spectral range of 220-1100 nm and spectral resolution of 0.2–0.5 nm registers plasma emission in the undisturbed zone of oncoming plasma stream ($\Delta Z \approx 0$–15 mm from the outlet of the plasma torch), and in the zone of interaction with the sample ($\Delta Z \approx 18$–20 mm). To obtain these emission spectra at the chosen distance $Z$ from the nozzle of the plasma torch a sharp image of the plasma torch is projected onto the focal plane of the fiber optic cable with a scale of 1 : 2 using a quartz lens with $f = 250$ mm. The input end of the Avaspec 3648 optic cable perpendicular to the plane of the image can be moved in this plane, and using collimator with a 1mm diameter hole can focus on the part of the image that is of interest to the research.

During the measurement cycle more than a hundred spectra of plasma emission were recorded at different coordinates, with expositions of 1–10 ms and spatial resolution of about 1 mm. To transform the recorded values into the absolute intensities a reference source (band tungsten
Figure 3. The characteristic emission spectra of the plasma (arc current 200 A): (on left-hand side) $\lambda \approx 350–620$ nm; (on right-hand side) $\lambda \approx 600–1000$ nm.

The registration of these spectra at 2–4 frames per second provides a detailed idea of the plasmas spectral composition and the emission intensities changes throughout the whole cycle of interaction [10]. As well, allows the use of spectroscopy pyrometric methods to investigate surface temperature of the sample [11]. Examples of characteristic spectra are shown in figure 3.

Acknowledgments
The work is supported by the Russian Ministry of Education as part of the Federal Program RFMEFI60414X0090.

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