Study of cooling process of plasma jet flowing around a thin ablating graphite rod

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Abstract. We present results of spectroscopic measurement of electron temperature in submerged nitrogen and argon mixture plasma jet for cases of free flow and introduction of thin graphite rod into the jet. The observed cooling of plasma caused by rod introduction agrees with the calculated enthalpy decrease from graphite rod heating and ablation. In this experiment, a marker was used to create artificial optical inhomogeneities in the flow, which allowed us to determine flow velocity from the analysis of their movement. In this case, we aim to determine the degree of influence of rod introduction into the plasma on its parameters. Upon introduction into the plasma, the rod was heated and partially destroyed by the plasma flow, reducing its temperature by 8-20% depending on the flow rate of the plasma-forming gas. The observed plasma cooling was compared with the calculated decrease in enthalpy caused by the cost of heating and ablation of the rod material.

1. Introduction. Analysis of the motion of optical inhomogeneities (OI) in gas and plasma jets with an unsteady flow allows measuring the velocity of the flow [1]. Most plasma installations use relatively short plasma jets with a length of several diameters of the output nozzle of the plasma torch at a subsonic (10-10³ m/s) speed. Natural OI appearing due to spatial inhomogeneity of the jet, stall flows in the output nozzle of the plasma torch, etc. can be easily registered in such flows by optical methods (high-speed visualization, Schlieren photography). By creating artificial OI, we make their formation systematic and become able to propose principles and an algorithm for determining their velocity. The method described in work [2] bears some similarities to our work, but uses an injected thin stream or single droplets of liquid rather than a solid rod. High-speed diagnostics utilizing particle trajectory analysis for velocity allow obtaining the trajectories of particles into which the injected droplets split. In work [3] velocity vectors of a turbulent plasma jet are measured from the movement of short-living formations created by laser impulses.

The most important problem of velocity measurement from introduced optical inhomogeneities is to minimize jet perturbations by the introduced probes. We pay special attention to this matter in our article. The proposed method of generating IO is to introduce a thin (d << D - jet diameter) heat-resistant rod into the jet perpendicular to the jet axis. Its slow decomposition in plasma creates a wide variety of large and small-scale OI. In order to minimize their perturbing effect on the moving plasma we need to experimentally elect the correct heat-resistant material and establish the conditions under which the
velocity of OI motion matches plasma flow velocity. In our experiments the velocity estimated by this method was 130-150 m/s. The technique and results are described in detail in the article [4].

In this paper, we consider the fundamental question of the perturbing effect of a foreign body introduced into plasma jet on its most important characteristic — the electron temperature.

![Experiment setup diagram](image)

**Figure 1.** Experiment setup. 1 – plasma jet, 2 – graphite rod, 3 – optical inhomogenities, 4 – rod introduction drive, 5 – DC plasmatron, 6 – fiber channel spectrometers.

2. **Measurement setup.**
Our experimental installation including graphite introduction system and measurement devices is shown in Figure 1.

A graphite rod (2) with diameter \(d=0.7\) mm can be introduced into the plasma jet (1) with diameter \(D (D>>d)\) by an electromagnetic drive (4) for the duration of 1 s or less. The plasma jet flows from an expanding output channel of a DC plasmatron (5) [5, 6] into the atmosphere. The rod is placed at a right angle to the longitudinal \((z)\) axis of the channel in 5 mm from its output nozzle. The plasma gas is a mixture of argon and nitrogen with mass ratio 9:1 and mass flow 1–4 g/s. Arc current can be adjusted between 200 and 400 A and arc voltage between 40 and 50 V, output nozzle diameter is \(D_o=8\) mm. The products of graphite rod ablation and evaporation by plasma jet are carried away by the jet and form long-existing light-emitting OI (3). Optical emission spectra are registered using AvaSpec 3648 fiber channel spectrometer with wavelength range 220–1100 nm and spectral resolution of 1 nm.

3. **Spectral analysis of thermal disturbance of the plasma jet caused by introduction of graphite rod.**
In order to experimentally determine electron temperature of the plasma near the introduced rod we registered optical emission spectra of the jet in 1–2 mm along the \(z\)-axis of the jet from the rod. The spectra were registered at the rate of 100 Hz with 2 ms exposition during the whole experiment duration.
from the start of rod introduction into the plasma to the end of its removal which lasted for about 600 ms. The lead-in and lead-out times of the rod were 20-30 ms.

Figure 2 shows optical emission spectra of the plasma jet before rod introduction (0 ms), while the rod is fully introduced in the jet (120–550 ms) and after its removal (620 ms). These spectra were obtained with plasmatron operating at $G = 1$ g/s, $I = 250\, \text{A}$, $U = 45$.

We can determine plasma temperature in the rod disturbance region during the whole experiment duration from the spectral bands of plasma gases N I and Ar I. Electron temperature matches the temperature of heavy particles in the free-flowing jet and can be determined by applying the relative intensities method to Ar I and N I spectral bands which have excitation energies $E_k$ that differ more than the expected temperature: $\Delta E_k > T_e$.

Figure 3 shows an example of excited level population for Ar I atoms obtained for the spectrum registered on 620th ms of the experiment. These distributions were obtained for each of the spectra shown in Figure 2. They indicate the validity of Boltzmann’s law for the distribution of atoms over excitation states. We determined that plasma temperature decreases in the rod disturbance zone by about 1500 K and recovers back to $T_e \approx 11000$ K after the rod is removed from the jet (see Figure 4).

4. Calculation jet enthalpy variation caused by rod introduction.

The temperature of the rod introduced into the jet was found to rise up to $T_w \approx 2600$ K from its heat emission spectrum in Wien coordinates.
Figure 3. Temperature determined by applying the Boltzmann exponent method to optical emission spectrum bands of Ar I at 620 ms. Determined temperature is $T_e = 11000 \text{ K}$.

Rod mass loss was determined by weighting it before and after the experiment and was found to be $\Delta m_{\text{abl}} \approx 2.5 \times 10^{-3} \text{ g}$. The energy required for ablation was found to be $\Delta W_{\text{abl}} = \Delta m_{\text{abl}} \cdot H_{\text{abl}} = 150 \text{ J}$ where $H_{\text{abl}} = 60 \text{ kJ/g}$ is the specific energy of graphite sublimation [7].

Specific heat flux in the jet cross-section of rod introduction measured calorimetrically was found to be $q_0 \approx 1.5 \text{ kW/cm}^2$. The right part of the energy balance equation for the rod surface includes terms accounting for rod material ablation and radiation energy loss at rod surface temperature $T_w$:

\[
q_0 \cdot S_R / 2 = \Delta W_{\text{abl}} / \tau_{\text{abl}} + q_R \cdot S_R = \Delta m_{\text{abl}} \cdot H_{\text{abl}} / \tau_{\text{abl}} + q_R \cdot S_R = 150 / 0.8 + \varepsilon \sigma T_w^4 \cdot \pi d_D \approx 220 \text{ W}
\]

Heat flux of these losses is

\[
W_{\text{loss}} = H_0 \cdot g \cdot S_{\text{rod}} / S_{\text{jet}} \approx 11 \frac{\text{kJ}}{\text{g}} \cdot 1 \frac{\text{g}}{\text{s}} \cdot 4 d_0 / \pi d_D = 1200 \text{ W}
\]

The relative decrease of jet power and enthalpy at 1 g/s gas flow is

\[
\frac{\Delta H_{\text{plasma}}}{H_0} = \frac{\Delta W_{\text{abl}}}{W_0} = \frac{220}{1200} = 0.18.
\]

The reduction of enthalpy in argon-nitrogen plasma by 18% at the following conditions of the experiment (Figure 5): temperature $T_0 = 11000 \text{ K}$ for 1 g/s gas flow and 10% nitrogen concentration gives temperature decrease by

\[
\Delta T_{\text{plasma}} \approx \frac{\Delta H_{\text{plasma}}}{C_p(T_0)} \approx 1600 \text{ K},
\]

where $C_p(T_0)$ is the mean heat capacity of the mixture at incident jet temperature $T_0$. This estimate agrees well with the experimentally measured cooling of the plasma (Figure 4).
Figure 4. Plasma temperature measurement results in the rod disturbance zone for whole experiment duration.

Figure 5. Total enthalpy of the jet for various nitrogen proportions and flow 1 g/s. The blue line shows power supplied to the jet.
Conclusions
Visualization of optical inhomogeneities in the plasma jet, both appearing naturally and artificially introduced, allows determining the velocity of a plasma jet. An analysis of the plasma emission spectra in the perturbation zone allowed us to establish the degree of plasma cooling during introduction of a graphite rod into it (by 800–1500 K), as well as to observe the recovery of the temperature back to the initial value of $T_0 = 11000$ K (with determination error less than 10%). Analysis of heat balance equation for the surface of the rod showed that the enthalpy of the incident plasma flow decreases mainly due to heat energy consumption by ablation of the rod material. In our case, spectroscopic measurements of temperature in the area around the rod are in good agreement with enthalpy calculation results for the gas mixture used in the work (90% Ar, 10% N).

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