Radiation of argon clustered flow particles outside the exciting electron beam

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Annotation. The spectral study results of a supersonic clustered argon flow stimulated emission in the region of particle excitation (on an electron beam) and downstream are presented. Anomalies in the luminescence of the traditional spindle-shaped jet and the flow of heavy clusters ("wake") are discussed. Possible causes of the observed anomalous phenomena are presented on the basis of the given comparisons of the results obtained.

1. Introduction
The study of nozzle outflows of gases and gas mixtures in a highly rarefied environment or vacuum is an urgent scientific and technical problem. One of the widely used methods for studying gas flows is electron-beam diagnostics, based on the excitation of particles by an electron impact and the subsequent registration of stimulated radiation. While the processes of excitation-emission of monomer flows are considered to be studied, the effect of condensation on them is still an open and unsolved problem.

In the course of experiments on the study of argon jets behind supersonic nozzles, it was found that, under conditions of developed condensation, in addition to a typical spindle-shaped jet, a secondary flow ("wake") of large dimensions is also observed (Fig. 1), which has a weakly damped anomalous glow of a different shade (in comparison with traditional jet) behind the excitation region [1].

Further studies [2] suggested that the reason for the "wake" appearance is the formation of large clusters in the flow, which are able to overcome the lateral shock waves and form their own parallel jet, also limited due to collisions with particles of the background medium. It was found that the

Figure 1. Visualization of argon jet escaping from supersonic nozzle in conditions of developed condensation by high-voltage electron beam. Stagnation pressure $P_0 = 0.4$ MPa, background pressure $P_b = 4$ Pa.
"wake" is not observed behind the sonic nozzles, at low stagnation pressures $P_0$ and in flows of weakly condensing gases (nitrogen, helium, etc.) in the absence of large clusters.

This report discusses the detected anomalies in the glow of clustered flows and cluster "wake" in the region of radiation initiation (on an electron beam) and downstream. The obtained profiles of the normalized radiation intensity are presented, and the possible causes of the observed phenomena are discussed.

2. Experimental setup
The work was performed on the LEMPUS-2 gas-dynamic stand of the Novosibirsk State University [3], the schematic diagram of which is shown in Fig. 2. A pre-chamber with a nozzle (1) is installed on a coordinate mechanism inside the expansion chamber (2). The gas flowing out of the supersonic nozzle forms a jet (3), the radiation of which is initiated by a high-voltage electron beam (4). Near the optical window (5) of the expansion chamber, a small-diameter quartz lens (6) is installed on its own coordinate mechanism. Lens focuses the image on the opening of the waveguide (7), which delivers radiation to the spectrometer (8). The lens coordinate mechanism made it possible to move the optical axis (a) and localize measurements along the jet axis (b) relative to the electron beam axis (c) downstream and register radiation not only in the region of radiation initiation, but also outside it.

![Figure 2. Schematic of the measuring system. Orthogonal axes: a: optical axis of the visualization system; b: axis of the supersonic jet; c: axis of the electron beam. 1 – gas source (pre-chamber with a nozzle); 2 – expansion chamber; 3 – supersonic jet; 4 – electron beam; 5 – optical window; 6 – quartz lens on coordinate mechanism; 7 – optical waveguide; 8 – spectrometer.](image_url)

3. Results and discussion
In the framework of the experiments, the change in the radiation spectrum of argon in a clustered flow was investigated when the localization of radiation was removed from the excitation region. The work demonstrates a spectral measurements presented in Fig. 3 and 4. The transverse profiles of the normalized radiation intensity of various argon lines (420.1, 461.0, 488.0, 549.6, 591.2, 603.2, 750.3, and 811.5 nm) was recorded in one flow section at a distance of 93.75 mm from the nozzle, i.e. behind the X-shaped configuration for the selected gas-dynamic parameters of the jet, in the region of the "wake" expansion, at different distances between the electron beam and the localization of measurements. The choice of argon emission lines is due to the following factors: high intensity, different spectral region, distinguishability from other transitions, different behavior in the "wake" radiation. Photometric measurements [4], carried out also for the used outflow mode (diameter of critical cross section of nozzle $d_*=0.17$ mm, $P_0=0.6$ MPa, $P_b=5$ Pa, stagnation temperature $T_0=320$ K), made it possible to determine the diameters of the traditional jet and cluster "wake" in the selected flow section.

Comparison of the transverse profiles of the radiation intensity recorded directly in region of the electron beam showed good agreement on all emission lines (Fig. 3,a). The received profiles correspond to the profiles obtained in monomer flows, and visualize only the traditional flow (the second "barrel" of jet), while the radiation of the cluster "wake" is not observed at all.
Having displaced the electron beam from the investigated cross section by 20 mm upstream, the radiation of the "wake" was discovered clearly (Fig. 3b). The boundaries of the "wake" recorded by the spectral method coincided with a good accuracy with the photometric measurements. However, it was found that the radiation intensity in the "wake" for argon lines is different. Not all argon lines are capable of responding to a "wake". No systematic dependence of the emission of excited neutral argon Ar-I (wavelengths 420.1, 549.6, 591.2, 603.2, 750.3, 811.5 nm) and ionized argon Ar-II (wavelengths 461.0, 488.0 nm) was found.

Figure 3. Comparison of the transverse profiles of the normalized radiation intensity $I_n$ recorded in a clustered argon flow at wavelengths 420.1 nm (violet line), 461.0 nm (blue), 488.0 nm (cyan), 549.6 nm (green), 591.2 nm (yellow), 603.2 nm (orange), 750.3 nm (red), and 811.5 nm (gray) at a distance of $x = 93.75$ mm from the nozzle exit when the exciting electron beam is displaced by 0 mm (a) and 20 mm (b) from the measurement localization upstream.

Figure 4. Comparison of the transverse profiles of the normalized radiation intensity $I_n$ recorded in a clustered argon flow at wavelengths of 549.6 nm (a), 603.2 nm (b), 750.3 nm (c), and 811.5 nm (d) at a distance of $x = 93.75$ mm from the nozzle exit when the exciting electron beam is displaced by 0 mm (solid line), 5 mm (intermittent line), 10 mm (dashed line), 15 mm (dash-dotted line) and 20 mm (dotted line) from the measurement location upstream.
Fig. 4 shows a comparison of the profiles recorded in the same flow cross section for 4 argon radiation lines at different positions of the electron beam relative to the localization of measurements. The measurement results show that the glow of the "wake" with distance from the excitation region weakens more slowly than the luminescence of the main jet, which indicates other relaxation and energy transfer processes in the cluster flow, which is also confirmed by measurements of the lifetimes of particles in an excited state [2].

The analysis of the obtained results of spectral measurements showed that, similar to photometric observations, the luminescence of the "wake" is most intensely manifested in the green, yellow and orange regions of the spectrum, and less intensely in the red and near infrared regions, which is reflected in the color shade of the cluster flow.

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