The condensation influence on the jet structure after supersonic gas expansion

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Abstract. The study of free supersonic jets showed that the condensation process leads to the Van-der-Waals clusters formation. Supersonic flows clustering leads to a change of the first jet dimensions and to the formation of a secondary structure (“trace”). When the jet is ionized by an electron beam, this structure has a weakly fading glow outside the ionization region. The authors of this work explore the processes leading to the formation of this glow. The condensation influence on the background gas penetration into the jet, the energy exchange effect between jet particles and background particles, and particle lifetime in the “trace's” glow process are studied.

1. Introduction
The free jet expansion into the region with a final background pressure is one of the fundamental processes of gas dynamics. This process has wide practical applications. The velocity vector of supersonic jet particles has a radial component. As a result, the gas jets escaping from the supersonic nozzle have a typical barrel-shaped configuration with the Mach disk. The boundaries of this structure satisfy the Rankin-Hugoniot equations. The interaction of the jet with the background gas leads to the formation of a mixing region between them.

Adiabatically expanding gas performs work against external forces at the expense of its own internal energy. During this process, the gas thermal energy is converted into the kinetic energy of the translational motion [1-2]. As a result, the gas temperature decreases to the saturation point, after which the condensation process begins. Formed at the first stage associates (“clusters”) increase their size until the appearance of crystal structures. The gas condensation process in a supersonic jet comes after reaching a parameter $P_0d_*^\alpha$ of a certain value ($P_0$ is the stagnation pressure, $d_*$ is the diameter of the nozzle throat cross section, $\alpha < 1$). Increase of the $P_0/P_b$ ratio (where $P_b$ is the background gas pressure) leads to a decrease of the Reynolds number $Re_L$ (1). As a result, the mixing region becomes blurred, and the background gas penetrates into the jet [3]. The Reynolds number $Re_L$ is defined as

$$Re_L = \frac{Re_*}{\sqrt{P_0/P_b}},$$

where the Reynolds number $Re_*$ is determined from the parameters in the nozzle critical section.
Since the mixing region of a supersonic jet consists of a monomer gas, large clusters formed during gas condensation can overcome the mixing region. As a result, after the transverse dimension maximum of the supersonic jet (the first "barrel"), a broader and elongated weakly luminous flow is observed. It has a “barrel” shape similar to the primary jet, but its dimensions are several times larger than the dimensions of the first "barrel" [4]. Obviously, this process occurs only for certain values of the Reynolds number $Re_l$ (when the momentum loss of cluster particles is smaller than its maximum value, under the condition that the average number of cluster collisions with background particles is limited). This structure is called "trace". This phenomenon was observed only in lightly condensable gases (argon, carbon dioxide, etc.) under conditions of developed condensation. Also, the average size of the clusters was higher than a hundred atoms.

An example of a supersonic jet with a "trace" is shown in figure 1. The argon jet flowing through the supersonic nozzle is crossed by a focused electron beam with energy of 10 keV. Collision of gas particle with electron leads to its excitation. Electrons of an atom pass to a higher energy level. As a result, a quantum of light is emitted. Particle radiation is observed even in the visible range. The predominant short-lived excited states radiate almost immediately (within $10^{-6}$ seconds). This fact explains the strong luminescence in the zone of the primary electron beam. Excited by scattered and secondary electrons long-lived levels cause luminescence outside the primary electron beam.

The "trace" transverse dimension exceeds the primary jet transverse dimension approximately by a factor of 2, and the longitudinal dimension by a factor of 6-7. The structure of the jet with a "trace" is not homogeneous. Excited by the electron beam radiation weakens away throughout the "trace". The mechanism of this luminescence has not yet been determined. There are various explanations for the reasons of this phenomenon:

- the flow of ionized clusters with luminescence of long-lived states,
- energy exchange within the cluster (energy distribution to individual atoms),
- collisional energy exchange of excited clusters with neutral background particles leading to spontaneous fluorescence of background particles.

The last option is considered in [5], where the possibility of the plasma-chemical conversion initiation of light hydrocarbons (but without binding to the gas dynamics of the "trace") was discussed.

The interaction processes between the background gas particles and the jet particles were considered in [3]. However, the condensation process influence on the jet in this work was not given. This process is directly related to the causes of particles luminescence in the "trace". In that regard, this work is aimed at deepening the study of processes that occur in a supersonic jet under increased condensation conditions.

2. **Experimental setup**

The present investigations were performed on a gas-dynamic complex "LEMPUS-2" based at the Applied Physics Department of the Novosibirsk State University [6].

The prechamber with supersonic nozzle is installed on the coordinate mechanism inside the expansion chamber. The conical nozzle parameters are as follows: the diameter of the nozzle throat

![](image.png)

**Figure 1.** Visualization of an argon jet by means of an electron beam. More bright areas correspond to more intense radiation in the visible range.
cross section \( d_c = 0.215 \text{ mm} \); the nozzle outlet section \( d_n = 3.5 \text{ mm} \); the nozzle length \( L = 17.5 \text{ mm} \). The electron beam crossed the jet perpendicular to its axis. It allowed ionizing the gas flow in the selected part of the jet.

The vacuum chamber is equipped with a quartz optical window, through which the radiation was observed. A stationary or mobile Optical System (OS) was located behind the optical window. The stationary OS consists of a fixed quartz lens with large diameter, which focuses the image of the jet investigated part to the entrance slit of the spectrometer. The jet axis, the electron beam axis and the optical axis are mutually orthogonal. This OS makes it possible to obtain spectra at the ionization point of the flow near the electron beam axis. The mobile OS is designed to record radiation along the axis of the jet, including region outside the electron beam (within the dimensions of the optical window). This OS consists of a small quartz lens located on its own coordinate mechanism. The radiation collected by the lens is focused on a waveguide connected to a spectrometer.

The vacuum chamber is equipped with an adding system, which makes it possible to change the composition of the background gas by adding any other gases to the residual working gas of the jet. Using a quadrupole residual gas analyzer ExtorrXT-300M (mass range: 0–300 u), the composition of gases in the background environment was monitored.

3. Results and discussion

3.1. Influence of clustering on the background gas penetration into supersonic flow

The linear Reynolds number \( Re_L \) (1), characterizing the ratio of the inertial and dissipative forces, determines the background gas penetration into the jet [3]. Therefore, the background gas penetration into different monomer jets with the same number \( Re_L \) should be the same.

To study the effect of condensation on the background gas penetration, two jets with the same Reynolds number \( Re_L \) must be compared. Argon (Ar) and carbon dioxide (CO\(_2\)) were chosen as test gases. The molar masses of the particles of these gases are close (respectively, 40 and 44 mg per mol). These gases have different degrees of condensation. According to this fact, clusters with different sizes will form in the jets of these gases. The theoretical calculation results of the necessary parameters are presented in table 1. According to this estimation [7], the clusters average size in jets with the same \( Re_L \) differs by an order of magnitude.

| Table 1. Comparison of supersonic jets parameters (test gases: argon and carbon dioxide). |
|---------------------------------|---------|---------|
| Parameter                       | Ar      | CO\(_2\) |
| \( P_0 \), kPa                  | 400     | 400     |
| \( P_h \), Pa                   | 3.72    | 1.97    |
| \( <N> \), un. per clust.       | 3700    | 24000   |
| \( X_L \), mm                   | 49.9    | 77.8    |
| \( Re_* \)                      | 18900   | 26000   |
| \( Re_L \)                      | 57      | 57      |

When the test gas flows into the rarefied space, the residual background pressure is created by particles of the same test gas. For determination of the background gas penetration into the flowing stream, a change of the background gas composition is needed. To achieve this goal, a nitrogen impurity was added to the background gas. Nitrogen has pronounced emission bands in transitions series \( N_2^+(\text{B}_2\Sigma_u^+ \rightarrow \text{X}_2\Sigma_g^-) \), (0-0, 391 nm). The background gas mixture was created as the partial pressures sum of the residual gas of the jet (Ar or CO\(_2\)) and the impurity gas (N\(_2\)) added additionally in the vacuum chamber. The percentage of the mixture components in the background gas remained...
constant. Any variance of the nitrogen radiation intensity (after subtracting the test gas contribution to the radiation) at different distances from the nozzle shows the background gas penetration into the jet.

The linear dimensions of the supersonic jets with the same number ReL differ (table 1). To compare the obtained trend lines, the dimensionless coordinate Xn (2) was introduced [8] as

\[
X_n = \frac{x}{d} \sqrt{\frac{P_0}{P_n}},
\]

where x is the linear coordinate, d is diameter of the nozzle throat cross section, P0 and Pn are the stagnation and background gas pressures.

The experimental result of comparison of the background gas penetration into the jets with different condensation degrees is shown in figure 2. The parameters of the jets in these measurements differed only in the mean cluster size <N>. However, despite the fact that jets have the same geometry (in the dimensionless coordinates), penetration degrees are different. It means that the parameters of the background gas penetration into the jet (and into the "trace" too) depend on the clusters size and on the condensation process in general.

### 3.2. Quenching of the luminescence

To study the particles radiation outside the ionization region, total spectra outside the electron beam were recorded. Measuring range was [0; 40] mm; measurement interval was 1 mm. Based on the obtained data, the intensity lines were plotted by points as a function of the distance to the ionization region Xn. The results of the measurements are shown in figure 3.

The slow decrease of the radiation intensity near the axis of the electron beam is explained by the finite size of the beam (1-1,5 mm) and the different lifetimes of the atoms excited states. Since the electron density in the beam is not uniform, the radiation intensity decreases with increasing distance to the beam axis.

Some conditions should be noticed. The ionization probability of the jet atoms or molecules by electrons is small (does not exceed 10⁻³-10⁻⁴) [9]. As a result, the ionized particles continue to move in the jet together with the neutral particles. The corresponding particle speed at the initial section of the primary argon jet (Xn = 0,15) shall not be higher than approximately 540 m/sec (and 670 m/sec for...
carbon dioxide). This fact does not exclude collisions between ionized and neutral particles inside the flow outside the ionization region. After the jet particles emerge from the ionization region, the radiation intensity in the flow at the initial section of the primary "barrel" is well described by an exponential with a fixed lifetime in the excited state. However, behind the disc of Mach this dependence has bimodality. It is suggested that the second mode appearance is explained by the influence of energy-exchange of "trace" particles with background gas particles on the radiation process.

**Figure 3.** Comparison and approximation (dashed lines) of the argon radiation intensity dependence (419 nm) downstream of the electron beam with different value $X_n$: 10 (squares), 100 (triangles) and 201 mm (circles). $P_h = 2.05$ Pa, $P_0 = 400$ kPa.

**Figure 4.** A comparison of the carbon dioxide radiation intensity dependence in different parts of the spectrum (288, 412 and 471 nm) downstream of the electron beam with value of $X_n$: 116.5 mm. $P_h = 1.97$ Pa, $P_0 = 0.4$ MPa.
Comparison of trend lines in the carbon dioxide jet (obtained at different wavelengths in the ultraviolet, violet and blue regions of the spectrum) has shown that the rate of the radiation intensity decrease outside the ionization region is also different (figure 4). This phenomenon can be explained by the difference of the particles lifetimes at the excited state. Figure 4 shows that the levels corresponding to radiation in the visible wavelength range are longer-lived than in the UV range.

4. Conclusions
In the course of the work, some difficulties that accompany the study of the luminescence of the "trace" outside the ionization region were revealed. Firstly, the effect of the cluster "trace" and the process of condensation in general on the background gas penetration into the supersonic jet was detected. In addition, bimodality in the process of fluorescence quenching outside the electron beam was revealed. Finally, a change of the particles emission spectrum outside the ionization region was observed. By our assumption, the cause of the glow in the "trace" is the energy exchange between the jet particles and the background gas particles. The effect of more locking the jet from the surrounding gas due to condensation is very important for understanding the processes occurring inside the jet.

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6. References
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