On the similarity of traditional and cluster jets during supersonic gas outflow into flooded space

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Annotation. The visualization of gas flows expanding from supersonic nozzles into flooded space under the cluster formation conditions is considered. The technique of exciting the supersonic flow by a well-focused high-voltage electron beam is applied in conjunction with the scanning equipment for the gas objects. The reasons for the secondary cluster jet formation in a flow of easily condensing gases are discussed. A comparison is made between the formation of a traditional spindle-shaped jet and a secondary cluster one. The measurement results of the diameters of the traditional and cluster jets in maximum sections, obtained by the photometry method, are presented. It is shown that for the characteristic sizes of cluster jets of condensing gases, the dependence on parameters proposed by Sherman and Ashkenas is applicable in the entire range of the studied stagnation and background pressures. The similarity of the formation processes of traditional monomeric jets and secondary cluster jets under the conditions of developed condensation of the initial supersonic flow is supposed.

1. Introduction

The gas jet formation behind supersonic nozzles is a widely studied physical process. Many scientific works provide a visual description of the structure of gas flows formed during the gas expansion from the nozzle into the flooded medium. A common distinguishing feature is the formation of the so-called “barrel” formed by side shock waves, the region of mixing of the jet particles with the surrounding background gas and the Mach closing disk or X-shaped configuration. Under certain conditions, a sequence of several “barrels” is formed [1-3].

A typical spindle-shaped structure with the formation of an X-shaped configuration is shown in Fig. 1 by the example of a supersonic nitrogen jet flowing out of a supersonic nozzle in conditions of weak condensation. The visualization of the flow is obtained by initiating emission of flow particles by an electron beam. Due to a large difference in particle density downstream, it is impossible to visualize the entire structure in one image. In this connection, the image obtained by the photo camera is divided into fragments with a comparable radiation intensity, which are converted by changing the brightness and contrast to better display the structural elements of the stream in the post-processing stage. A spindle-shaped structure, observed in Fig. 1, is typical for supersonic gas jets. However, according to [4], it is not the only possible one. Under conditions of developed gas condensation in the jet, when large clusters are formed, another parallel structure of significantly larger sizes (in comparison with the traditional “barrel”) is formed behind the supersonic nozzle. This structure is detected in an argon flow in a certain
range of initial parameters of the outflow (Fig. 2). A new structure could also be visualized in carbon dioxide flow.

This structure is assumingly formed due to the passage of heavy clusters through side shock waves and the mixing region with the formation of additional cluster jet. Due to the low binding energy, clusters under collisions (with flow particles or particles in the background medium) undergo fragmentation, as a result of which the boundaries of the cluster jet also close on the flow axis into an X-shaped configuration, forming a “barrel” of large sizes, similar to traditional one.

This work considers the similarity of a traditional and cluster jet by the method of photometry using an example of a comparison of the diameters of “barrels” formed in various outflow modes.

2. Experimental setup
The work is performed at the gas-dynamic stand LEMPUS-2 of Novosibirsk State University [5], the schematic diagram of which is shown in Fig. 3. A pre-chamber with a nozzle (1) is located on coordinate mechanism inside the expansion chamber (2). The gas flowing from a supersonic nozzle forms a jet (3). Radiation of jet particles is initiated by a high-voltage electron beam (4). Next to the optical window of the expansion camera (5), a photo camera (6) is installed. Monitoring of the processes in expansion chamber is carried out by taking pictures. The dimensions of the “barrels” are determined by the method of photometry, based on a comparison of the flow structural elements with the construction detail of the nozzle pre-chamber of a known diameter observed in the expansion chamber. The reasons for the long afterglow of gas objects outside the electron beam and the probable causes of the abnormal glow of the cluster jet were previously described in [6].

Figure 1. The visualization of a single supersonic nitrogen jet flowing from a supersonic nozzle with the parameters $d^{*} = 0.256$ mm; $P_{0} = 0.6$ MPa; and $P_{b} = 6$ Pa. Here $d^{*}$ is the diameter of the nozzle’s sonic critical section, $P_{0}$ is the stagnation pressure in nozzle pre-chamber, and $P_{b}$ is a pressure in the background medium.

Figure 2. The visualization of an argon flow with additional cluster jet flowing from a supersonic nozzle with the parameters $d^{*} = 0.256$ mm; $P_{0} = 0.4$ MPa; and $P_{b} = 5$ Pa.

Figure 3. 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 – photo camera.
3. Results and discussion

Based on the assumption that the secondary structure formation takes place in the condensation conditions, during the study of argon flow, two series of measurements of the diameters of the traditional jet $Z_j$ and cluster jet $Z_w$ in the maximum cross section were carried out (1) with varying gas pressure in the background space $P_b$ and fixed pressure $P_0$ and stagnation temperature $T_0$, when the average cluster size $\langle S \rangle$, estimated according to [7], did not change, and (2) with variation of $P_0$ and fixation of $P_b$ and $T_0$, when the clusters increased in size. The outflow parameters in the measurements are presented in Table 1.

Table 1. Parameters of argon outflow from a supersonic nozzle with $d^* = 0.256$ mm.

| Modes number | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $P_0$, kPa   | 100 | 200 | 400 | 600 | 800 | 400 | 400 | 400 | 400 | 400 |
| $P_b$, Pa    | 3   | 3   | 3   | 3   | 3   | 3   | 1   | 2   | 3   | 4   |
| $\langle S \rangle$, particles per cluster | 60  | 300 | ~1500 | >4000 | >6000 | ~1500 | ~1500 | ~1500 | ~1500 | ~1500 |
| $Re_L$       | 31  | 44  | 62  | 75  | 87  | 36  | 50  | 62  | 71  | 79  |

The results of the first series of measuring the diameters $Z_j$ and $Z_w$ (modes 1.1–1.5) with $P_b$ variation have confirmed the linear dependence of the value $d^* \sqrt{\frac{P_0}{P_b}}$ presented in [8] (Fig. 4). It should be noted that both the traditional and cluster jets increased in size in accordance with their constant proportionality coefficients.

The second series of measurements (modes 2.1–2.5) has revealed that it was impossible to describe similar dependences by a linear function when pressure $P_0$ varies (Fig. 5). However, the form of the obtained dependences for the traditional and cluster jets is identical, that indicates the similarity of the processes of their formation. It is noteworthy that the proportionality coefficients in this series of measurements increase with increasing $P_0$. Since, as is known, the cluster size grows with increasing $P_0$ [7], it is suggested that the size of the jets (and the proportionality coefficient) depends on the size and proportion of clusters in the jet. The possible corrections to the Ashkenas-Sherman’s dependence [8] are now considered, taking into account the increase in cluster size and the proportion of condensed particles.

![Figure 4](image-url) Figure 4. Approximation of the results obtained when measuring the diameters of traditional $Z_j$ (a) and cluster $Z_w$ (b) jets in their maximum cross section with $P_b$ pressure variation (modes 1.1-1.5).
**Conclusion**

This paper presents the measurement results of traditional and cluster jets sizes in various outflow regimes, on the basis of which an assumption of their similarity is made.

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**Figure 5.** Approximation of the results obtained when measuring the diameters of traditional $Z_j$ (a) and cluster $Z_w$ (b) jets in their maximum cross section with $P_0$ pressure variation (modes 2.1-2.5).