Laboratory simulation for single and block supersonic jets

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Abstract. Model experimental studies are presented for the flow field of a single jet, the flow parameters of a block jet, the pressure distribution on the bottom screen, and the parameters of the jet flow from a model nozzle. When expanding into a vacuum and/or a highly rarefied medium, the conditions for reproducing the relative gas pulse value of the full-scale nozzle block section are met. It is shown that when using specific similarity criteria, it is possible to experimentally model the supersonic jet outflow processes of space vehicles on small-sized laboratory vacuum installations, similar to the one created at Novosibirsk State University. Simulation results using spectral density measurements based on the glow excited by a focused electron beam, longitudinal and transverse jet density profiles obtained using modern scanning technology, as well as measurements of bottom pressure near the nozzle block are given. The possibilities and features of each applied registration method are discussed.

1. Introduction
Prospects for the aerospace technology development are currently associated with the development of a new spacecraft generation. This also applies to SmallSat and CubeSat micro devices due to their simplicity, low cost of manufacturing and launching into space. Programs for creating control and orientation engines for new spacecrafts for flights to the Moon, Mars and other planets of the Solar system are being actively developed. The creation of such devices is impossible without solving a number of fundamental scientific problems related to the high-speed flows gas dynamics, which are critical for the creation of future space vehicles samples.

Laboratory simulation of supersonic jets expanding from the nozzles of rocket engines is an integral task in the design and creation of new models of rocket technology. Specialized enterprises and large national production facilities have their own experimental base that provides testing of individual elements and units of spacecraft in conditions close to full-scale [1]. However, such tests, especially when simulating processes in a high vacuum or highly rarefied environment of complex gas composition, require extremely high capital and material costs. Therefore, the steps aimed at modeling complex supersonic flows in a vacuum on laboratory stands that are limited by the speed of pumping out the expiring gases are of interest. Such work is also carried out on the low-density gas-dynamic installations complex of the Thermophysics Institute SB RAS created in the 1970s-80s of the last century.
[2-3]. Unfortunately, current economic problems do not allow us to significantly modernize the pumping equipment and experimental diagnostic base of these installations. Another way to solve the problem for ground-based modeling of natural processes is to switch to short-term pulse systems of gas flow [4]. An obstacle to this approach is the difficulty for achieving similarity between pulsed and stationary flows [5]. As a result of filling the vacuum volume with slowly pumped residual gas, the gas dynamics of the flow has time to change significantly. To level the process, it is necessary to increase the volume size of the installations, which causes problems similar to those mentioned above.

Another method for ground-based modeling of jet outflow processes in outer space and rarefied planetary atmospheres has been used in recent years to miniaturize model conditions. As it is known, the kind of jets in the ideal gas expansion model is determined by the equality of the Mach numbers on the nozzles output $M_0$, relationship of specific heats $\gamma$, the nozzle diffuser angle $\theta_0$, as well as the relationship of gas pressure at the nozzle exit, $P_0$, and the pressure in the background space, $P_b$ [6]. The most serious problems arise when choosing the modeling gas with specific heat capacities ratio, $\gamma$, that is to correspond to the $\gamma$ of high-temperature combustion products. Mismatch of this parameter in the modeling gas with the natural one leads to significant errors in modeling.

The transition to the integral similarity parameters proposed in [7-8] allows decreasing the influence of $\gamma$ on the simulation results. It is shown that the similarity parameter for jets expanding into a vacuum or highly rarefied space is the value of the relative gas pulse at the nozzle throat $J = J(M_0, \gamma)$ or the characteristic angle of the flow field $\theta^* = \theta(J)$. If the proposed parameters are equal, the model jet reproduces the geometry of the flow field of the natural jet, and a similarity is realized in the distribution of the main parameters of the gas flow.

It is extremely difficult for simulation on laboratory installations to provide high temperature stagnation condition ($T_0$) in the nozzle pre-chamber for stationary or quasi-stationary supersonic flow. As a rule, on laboratory installations $T_0$ does not exceed 300-350 K. At high stagnation pressures, this leads to gas condensation in the simulated flow. The influence of condensation processes on the supersonic flowing can lead to a significant change in the gas dynamic parameters of the modeled flow. In these conditions it is extremely important to verify the simulation process.

In this paper, we present the results of modeling of single and block jets under conditions of similarity to some natural parameters given as an example. The jet experimental simulation on a small-sized vacuum unit was performed under different conditions for stagnation pressure with a single nozzle, i.e. in different modes for condensation. A high-voltage electron beam was used to visualize gas-dynamic flows with the developed scanning system. Modern spectral equipment served to determine the absolute values of local density in gas flows. Using molecular beam mass spectrometry, the presence of clusters in the flows was estimated, and a special sensor was used to measure pressure near the bottom plane of the nozzle block. Some of the results obtained, as well as the experience gained and the possibilities of using small-sized stands for modeling complex flows are presented and discussed below.

2. Experimental equipment
The research was carried out at the multi-functional gas-dynamic stand LEMPUS-2 of the Applied Physics Department of the Novosibirsk State University [9], designed, in particular, to work with increased gas consumption while maintaining a high vacuum in the working chamber. The setup is provided with high-vacuum high-performance and oil-free pumps, which allowed reaching the maximum mass flow rate of vacuum pumping on carbon dioxide of ~ 0.2 g/s in a continuous mode at an ambient pressure below 0.1 PA. Conducting experiments on the setup requires orders of magnitude less energy and supply materials than on the known large gas-dynamic installations of the second half and the end of the 20th century, both in continuous and pulsed flow modes. The simulation of expansion of supersonic jets of gases and gas mixtures was carried out using miniature submillimeter sized nozzles.

The equipment and diagnostic methods used in the stand are based on the jet visualization with the photographic image fixation and spectroscopic methods for measuring the flow fields parameters under electron-beam excitation of gas, flowing from a stationary or moving nozzle according to a given program. The electron beam of the stand's electron-optical system was focused to a diameter of less than
1 mm. This allowed obtaining physically thin longitudinal and cross sections of the jet to determine their local density. A diagnostic system using a modern scanner has also been developed to visualize the gas jets. This system provided a scan of the gas jet image in on-line mode.

Reducing the size of gas jets flowing from the nozzles slightly increased the methodological errors, but at the same time simplified the jet flows diagnostics for qualitative and quantitative measurements of longitudinal and transverse density fields using non-disturbing methods.

3. Results and discussion

Several measurement options are considered: photometry of the studied jets, obtaining flat longitudinal and cross sections of gas flows, as well as density fields using a modern scanning system with the result presentation in the form of illustrative material, density fields measurement in the jets using electron-beam spectroscopy, and back pressure measurement near the nozzle block using a special pressure sensor.

3.1. Photometry

In model experiments, cold, and therefore nonluminous, gas flows are used. At the same time, when expanding into a vacuum in supersonic jets, the density rapidly decreases, so that Schlieren research methods, widely used in wind tunnels for modeling flows at pressures corresponding to low altitudes, are unsuitable. Therefore, to visualize such flows, it is necessary to excite radiation in the jet. In most cases, a high-voltage electron beam is used as an excitation source [10]. Since long-lived levels in gases are also excited by electrons with energy of above 1 KeV, spontaneous radiation can be observed throughout the entire jet. If electrons collide with atoms or molecules of the jet, the excitation probability is low, so for a more intense radiation, the electron beam is set as close as possible to the nozzle throat, in the range of higher gas density.

An example of this visualization is shown in figure 1. A nitrogen jet is expanded from a single supersonic conical nozzle with parameters: the diameter of the critical throat \(d_\star = 0.215\) mm, the diameter of the output section \(D_a = 3.80\) mm, and the length of the diffuser \(L_{\text{diff}} = 17.0\) mm. The result was obtained at the stagnation pressure \(P_0 = 200\) kPa and the background gas pressure \(P_h = 8.7\) PA. Parameters of the exciting electron beam: electron energy \(E_e = 15\) keV and beam current \(I_e = 17\) mA. The electron beam is deliberately defocused to expand the primary illumination area.

![Figure 1. Supersonic nitrogen jet. High-voltage electron beam illumination.](image)

- \(L\) – the known size of the nozzle part; \(Z_j\) and \(X_j\) — the transverse and longitudinal dimensions of the first barrel of the supersonic jet, respectively.
- 1, 2, 3, — possible position of the border of the first barrel

In the left part of the photograph there are clearly visible elements of the pre-chamber nozzles, defining the true size of the jet. There are a fusiform structure of the supersonic jet, a mixing zone (brighter stripes on the sides), and an x-shaped configuration finishing the first barrel. Numbers indicate possible options for the border of the first barrel. It should be taken into account that photography is done from the side, and although the electron beam is perpendicular to the jet axis, the estimation of density changes in different parts of the jet is hindered by illumination from the side edges. As experience has shown, such photos provide information about the shape of the simulated flows and, as a rule, are not used for quantitative jet parameter measurements, except for their geometric parameters [11].
3.2. Spectroscopy

Another well-known method for determining density distributions in the field of expiring jets [12] is to use spectral measurements of the radiation intensity at a selected wavelength (for atomic gases) or the integral intensity of the vibrational band (for molecular gases). A mandatory condition, which in reality greatly restricts the choice of the spectrum section, is the absence of overlap with other bands, or with another gas in the event of mixture jets. However, in some cases, such measurements are quite accurate. An illustration is figure 2, which shows measurements of longitudinal profiles of the graded molecular nitrogen density as a function of electron beam - sound nozzle distance at different values of P0.

![Figure 2](image_url)

**Figure 2.** Influence of pressure P0 on the distribution of numerical nitrogen density on the jet axis. Diameter of sound nozzle d. = 0.5 mm. The spectral band λ = 391 nm.

Comparison of isentropic calculation with measurements of longitudinal profiles of molecular nitrogen density at different distances from the sound nozzle and several P0 has shown a slight deviation from the isentrope at a physical distance of less than 10 mm from the nozzle throat. This is due to electromagnetic interference of the grounded pre-chamber to the electron beam, as well as partial collision fluorescence quenching at high density level. At distances x/d* > 100, when approaching the Mach disk the background gas penetration to the jet is effected. In general, the coincidence with the isentropy is very good, which confirms the possibility of measuring density distributions in jets by electron-beam spectroscopy on small-sized installations and with miniature nozzles.

3.3. Scanning

Photo registration of longitudinal and cross sections of supersonic flows began to be used in studies of gas dynamics of supersonic jets shortly after the application of high-voltage well-focused electron beams for local measurements of the rarefied gas density [10]. The operation principle of this method was to move a gas object relative to a stationary electron beam with simultaneous coordinated movement of a photographic film, and the radiation excited by this beam was focused using an optical system. In the future, using densitometry of photographic film, researchers will obtain the desired scans of gas jets. This technique is particularly well suited for the study of the field density for the multiple nozzle arrangement of the gas jets expanding into the low-pressure area [3].

We propose and implement transition to modern registration technology. As a radiation detector, a manual image scanner is used, which is a line of photo sensors with a length of about 200 mm, providing a resolution of up to 900x900 dpi. Information is read on-line into a micro-SD card. This creates a file with digital data, which can be represented as an image of a luminous object, or as graphs of density changes for the selected coordinate. An example of such images when the working gas flows through the block of eight supersonic gas sources is shown in figure 3.

Below are the longitudinal (figure 3-a) and cross (figure 3-b, 3-c, 3-d) flow sections. The images were taken with a gray light filter to eliminate saturation of the scanner's photo sensors in areas with maximum gas density. The scanning speed was 2 mm/s. The temperature of the nozzle block T0 = 300 K. The stagnation pressure of the pre-chamber P0 = 100 kPa and of the surrounding background gas Ph = 0.5 Pa. Electron energy Ec = 10 Kev, and current Ie = 30 mA. The diameter of the electron beam did not exceed 1 mm. The advantage of this measurement method is the rapid acquisition of information in
digital form, which allows obtaining graphs of density distributions along the lines of interest almost in real time and with high resolution.

Figure 3. Scanned images of longitudinal (a) and transverse (b), (c), (d) profiles of a composite jet flowing from a square nozzle block.

Conclusions
The possibility of using methods and tools for diagnostics of supersonic flows that flow from single nozzles and nozzle blocks into a vacuum, highly rarefied medium, and flooded space on a small experimental installation of Novosibirsk State University are demonstrated. The existing equipment and developed methods can be used for modeling processes in the development of new-generation aerospace systems.

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