Simulation of the spacecraft supersonic jets in vacuum on small-sized laboratory installations

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Abstract. The paper presents the experience of modeling supersonic jets of rarefied gases expanding into a vacuum or highly rarefied medium of any given gas composition, as well as interacting flows from nozzle blocks on experimental installations developed at Novosibirsk State University. Examples of visualization of complex sparse flows, results of measurements by electron-beam spectroscopy and molecular-beam mass spectrometry of the density and flows composition under different flow conditions are given. The obtained experimental data validation problems and natural conditions modeling possibilities on small-sized laboratory installations, model and real flows conditions and parameters of similarity are discussed.

1. Introduction
The prospects for the aerospace technology progress are currently associated with the development of a spacecraft new generation. This applies to both transport vehicles to reach planets, and micro-devices in the SmallSat and CubeSat format. The problem of creating new types of control and orientation engines is actively discussed. The such devices creation is impossible without solving a number of fundamental scientific problems of high-speed flows gas dynamics, which are critical for the construction future samples of aerospace techniques. Laboratory simulations in this area will allow us to reproduce and study the flows distribution and the jets gas-dynamic interaction with each other and with the design elements of spacecraft.

Experimental research of the real spacecraft engines operation in vacuum conditions requires huge material and financial expenses. In the second half of the last century, large high-performance vacuum installations and complexes were created at Novosibirsk under Alexey Kuzmich Rebrov leadership to simulate the natural jet flows distribution from engines and to study the rarefied gases flow around devices [1–2]. Even earlier, similar work began at Leningrad under Sergei V. Vallander leadership [3]. However, the operating troubles of such complexes, the need in large capital investments for their modernization and equipping with modern vacuum pumping systems and diagnostics, and the high cost of each experimental startup led to the search for simpler and cheaper options of the experimental research.

We have considered the possibility of the supersonic jet experimental simulation from spacecraft nozzles under conditions of variation in the pressure of a rarefied medium and different compositions of gas atmospheres on compact small-sized experimental installations with limited performance of vacuum pumping systems. This paper describes the experience of the Novosibirsk State University (the Applied Physics Department) on the use of various operating options at such installations for modeling gas-dynamic jets, suggests ways to solve emerging problems, and provides measurement
methods used in experiments. The equipment is used for modeling the processes that accompany the gases outflow from supersonic nozzles, the gas jets expansion from a single nozzle and a multi-nozzle unit into a vacuum or highly rarefied space.

2. Experimental equipment and techniques

The research was carried out at multifunctional gas-dynamic installation LEMPUS-2 of the Novosibirsk State University [4], designed, in particular, to work at high gas consumption while maintaining a deep vacuum in the working chamber. The installation is provided with high-vacuum high-performance and oil-free pumps, which allowed to achieve the maximum vacuum pumping velocity on carbon dioxide at a continuous flow of ~ 0.2 g/s, at a pulse flow-up to 10 g / s at an ambient pressure below 0.1 PA. Conducting experiments on the installation requires orders of magnitude less energy and consumable 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 modes. Simulation of the supersonic jets outflow of gases and gas mixtures was carried out using miniature submillimeter-sized nozzles. The appearance of the installation, as well as parts of the equipment located inside the vacuum chamber, are shown in figure 1.

![Figure 1. LEMPUS-2 installation. (a) – the vacuum expansion chamber, top view ; (b) – view through the open hatch.](image)

Simulation on experimental installations requires determining the conditions for the jet outflow of spacecraft engines depending on the parameters of working gases and supersonic nozzles. Real rocket jets are sources of high-temperature combustion products. For such jets, the reproduction of the specific heat capacities ratio during the transition to "cold" flows of the model gas is practically unrealistic. Therefore, for laboratory experiments, it is necessary to find similarity criteria by which it would be possible to carry out approximate the natural processes modeling. It is customary to choose the nozzle geometry, the Mach number at the nozzle exit, the gas type, the temperature, the stagnation pressure, the pressure in the nozzle exit, the gas flux in to the vacuum and the nozzle opening angle.

The most serious problems arise when choosing a modeling gas whose specific heat capacity ratio \( \gamma = \frac{c_p}{c_v} \) may not always correspond to the \( \gamma \) of high-temperature combustion products. Mismatch of this parameter for the model gas with the natural one leads to significant errors. The authors [5] proposed a transition to integral similarity parameters that make it possible to bypass the influence of \( \gamma \) on the simulation results. It is shown that the similarity parameters for jets flowing into a vacuum or highly rarefied space are the value of the relative gas pulse at the nozzle throat and the characteristic angle of the flow field. If the proposed parameters are met, the model jet reproduces the flow field geometry of a full-scale jet, i.e. similarity in the distribution of the gas flow main parameters is realized.
3. Experience of Novosibirsk State University

The equipment and diagnostic methods used at the LEMPUS-2 installation are based on the jets visualization with the photographic image fixation, spectroscopic methods for measuring the flow fields parameters under electron-beam gas excitation with a stationary or moving nozzle according to a given program, as well as molecular-beam methods. The paper considers a number of options for studying gas flows: the studied jets photometry; obtaining flat longitudinal and gas flows cross sections, as well as density fields using a modern scanning system with the results presentation in the form of illustrative material; density fields measurement in jets using electron-beam spectroscopy, bottom pressure measurement on the wall of the nozzle or nozzle block, determination of the velocity, translational temperature and mass composition of the studied flows with molecular beam equipment.

In model experiments, cold gas flows are used, respectively, not luminous. At the same time, when expanding into a vacuum in supersonic jets, the density rapidly decreases, so that shadow research methods, widely used in wind tunnels for modeling flows at pressures corresponding to low altitudes of the earth's atmosphere, 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 [6].

The electron beam of the stand's electron-optical system was focused to a diameter of less than 1 mm. This made it possible to obtain physically thin longitudinal and the jet cross sections to determine their local density. A diagnostic system using a modern scanner has also been developed to visualize the gas jets flow field. This system made it possible to gaining a gas jet image scan directly during experiments.

3.1. Photometry

Since long-lived levels in the gas are also excited by electrons with energy above 1 keV, spontaneous radiation can be observed throughout the entire jet. The probability of excitation when electrons collide with particles of the jet is low, so for a more intense glow, the electron beam must be located as close as possible to the nozzle throat, in the higher gas density region.

An example of this visualization the nitrogen jet glow expanding from a single supersonic conical nozzle is shown in figure 2. The result was obtained at the stagnation pressure $P_0 = 200$ kPa, the background gas pressure $P_h = 8.7$ Pa. Parameters of the exciting electron beam: energy $E_e = 10$ keV, beam current $I_e = 17$ mA. The electron beam is deliberately defocused to expand the primary illumination area. In the left part of the photograph are clearly visible elements of the nozzle pre-chamber. The image shows the overall dimensions of individual elements. It can be seen a fusiform structure of the supersonic jet, a mixing zone (brighter stripes on the sides), and an X-shaped configuration that closes the first barrel. Note, however, that the photographing is conducted on the side, although the electron beam crosses the stream perpendicular to the axis. The illumination from the side edges prevents to registered of the real brightness in different parts of the jet. According to the experience, such photos provide information only about the shape of the simulated flows, and can not be used for quantitative jet parameters measurements, except for their geometric parameters [7].

![Figure 2. The supersonic jet of nitrogen. High-voltage electron beam illumination. L, D – longitudinal and transverse dimensions of the known part of the nozzle (for scale); Xj, Zj – longitudinal and transverse dimensions of the primary supersonic jet.](image-url)
of radiation excited by a narrow electron beam in a longitudinal or cross-section, with appropriate calibration and accounting for edge effects, provides information about the distribution of emitters in the selected band. When moving the jet to new positions and repeating the measurement process, you can get an image of the longitudinal or cross-section of the jet in units of radiation intensity or, when calibrating, the density distribution in the jet. An example of a supersonic jet image obtained by the described method is shown in figure 3.

**Figure 3.** Composite image of the argon jet, "stitched" from photos obtained by scanning the flow in the longitudinal section. The minimum width of the beam scan is 20 mm, the scanning step is 10 mm. $P_0 = 1200$ kPa, $P_h = 0.4$ Pa, $T_0 = 295$ K, $E_e = 10$ keV, $I_e = 25$ mA.

Despite the rather rough cross-linking, such photos can be used to determine the luminance intensities, and in turn, with appropriate calibration, the stream density.

### 3.2. Spectroscopy

Another well-known method for determining the density in jets is to use spectral measurements of the fluorescence intensity at a selected wavelength (for atomic gases) or the integral intensity of the vibrational band (for molecular gases). The condition that strongly restricts the spectrum section choice is the overlap absence with other bands, or with another gas in the event of a mixtures outflow. However, in some cases, such measurements are quite accurate. An illustration is figure 4, which shows calibrated longitudinal profiles measurements of molecular nitrogen density at the expansion from the sound nozzle at different values of $P_0$. The empirical formula [8] for comparison with the isentropic calculation is used.

**Figure 4.** Influence of $P_0$ pressure on the distribution of numerical nitrogen density on the jet axis. Sound nozzle $d_* = 0.5$ mm.

### 3.3. Scanning

Longitudinal and cross-sections photo registration of supersonic flows began to be used in studies of supersonic jets gas dynamics shortly after the application of high-voltage well-focused electron beams for the rarefied gas density local measurements [9]. We have proposed and implemented a transition to modern registration technology. As a radiation detector, a manual image scanner is used, which is a photo sensors line with an about 200 mm length, providing an up to 900x900 dpi resolution.
Information is recorded on the SD card. A file is generated with digital data, which can be represented as a luminous object image, or as a density changes graphs for the selected coordinate. A such images example for flows through a square arrangement of supersonic gas sources is shown in figure 5.

![Figure 5](image)

Figure 5. Scanned images of longitudinal (a) and transverse (b) sections of a composite jet flowing from a square set of nozzles.

3.4. Molecular beam methods
Correct skimming of the molecular beam from a supersonic stream allows us to register the molecules velocity distribution function and, accordingly, the velocity and translational temperature [10], and with the help of a mass spectrometer - the mass composition [11] in the studied jet. The report considers examples of measurements of supersonic flows of various compositions using molecular beam mass spectrometry in combination with electron beam spectroscopy.

4. Conclusions
The possibilities of using diagnostics of supersonic flows from single nozzles and nozzle blocks into vacuum, highly rarefied, and flooded space on a small-sized experimental installation for the purpose of modeling new-generation aviation and space systems being developed are demonstrated.

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