Problems of Gas-Dynamic and Contaminating Effect of Exhaust Plumes of Orientation Thrusters on Space Vehicles and Space Stations

Yury.I. Gerasimov[1], Vyacheslav.N. Yarygin[2]

1 - Korolev Rocket and Space Corporation ENERGIA, Korolev, Russia
2 - Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia
yarygin@itp.nsc.ru

Abstract. A review of results of the joint researches performed on this topic within the last 30 years at the Korolev Rocket and Space Corporation Energia (RSCE) and at the Kutateladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences (IT SB RAS) is presented.

Key words: Space vehicles, orientation and control thrusters, exhaust plumes, contamination processes, modeling in vacuum chambers.

INTRODUCTION

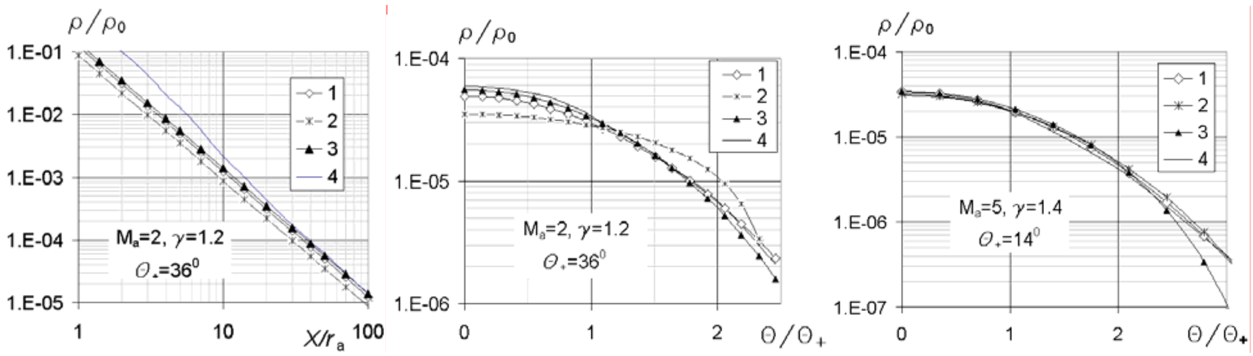
Exhaust plumes of control and orientation thrusters exert dynamic, thermal, and physicochemical effect on the ambient atmosphere and external elements of space vehicles and space stations. Research of these phenomena and processes is an important and necessary stage of development, creation, and operation of space vehicles and orbital stations. As the researches under real conditions are extremely expensive and not always possible, the basic attention is given to numerical and experimental modeling. Appearance of new concepts and problems in outer space exploration stimulates further improvement and development of both experimental and theoretical approaches for modeling plumes of orientation and control thrusters of space vehicles and orbital stations. Several issues associated with formulating and conducting experimental researches on the given problem are considered. The main attention is paid to development of new approaches to vacuum-chamber simulation of exhaust plumes of orientation thrusters and their interaction with adjacent surfaces. Issues of diagnostics and results of researches of jets under conditions of significant influence of nonequilibrium processes are considered. Results of the researches performed within the framework of particular programs, including the International Space Station, are described.

EXHAUST PLUMES MODELING CRITERIA

It is common practice in model researches of exhaust plumes to use the Mach number M_a and the ratio of specific heats γ as the governing parameters. Our researches [1] show, however, that nonequilibrium processes, such as homogeneous condensation and vibrational relaxation, alter the Mach number at the nozzle exit cross-section M_a and the ratio of specific heats γ. In this situation, it is expedient to use an integral parameter: a typical angle of jet divergence Θ_+ determined via the relative impulse $\bar{J}$ of the gas jet at the nozzle exit cross section [2]

$$\theta_+ = arctg\sqrt{(1-\bar{J})/\bar{J}} \qquad \bar{J} = J_a/(G_* \cdot V_{\max}) \tag{1}$$

where J_a, G_*, $V_{\max}$, and γ are the gas impulse at the nozzle-exit section, flow rate, maximum gas velocity in the jet, and ratio of specific heats, respectively. For adiabatic perfect gas flows, $\bar{J}$ it is determined by the values of γ and M_a [2].



(a) (b) (c)

FIGURE 1. Results of gas density calculations along the jet axis (a) and along an arc of a circle of radius r/r_a =50 (b, c): *1* – formula (2), *2* – L. Roberts' model [3], *3* – F. Albini's model [4], *4* – calculations with the method of characteristics.

Within this model, the distribution of gas density and dynamic pressure in an undisturbed jet $(\bar{r} = r/r_a > 10)$ are described as

$$\frac{\rho}{\rho_0} = \frac{0.21\cdot(\gamma-1)^{0.5}}{\bar{F}\cdot\bar{r}^2\cdot\theta_+^2}\exp(-0.5\cdot\bar{\theta}^2)\,, \qquad \bar{P}_0^I = \frac{P_0^I}{P_0} \approx \frac{0.42\cdot A_\gamma}{\bar{F}\cdot\bar{r}^2\cdot\theta_+^2}\exp(-0.5\cdot\bar{\theta}^2)\,, \qquad A_\gamma = \frac{\gamma}{(\gamma-1)^{0.5}} \tag{2}$$

where $\bar{\theta} = \theta/\theta_+$, r and θ are the polar coorditanes, $\bar{F} = (r_a/r_*)^2$.

The density calculation results in jets of an ideal gas according to this model are compared with data of other models in Fig. 1. It is seen that formula (2) allows calculating the value of gas density in a jet flow field with better accuracy than the formulas of L. Roberts and F. Albini. This is especially noticeable for small values of M and γ (Fig. 1a, 1b). In hypersonic jets (Fig. 1c), the results calculated according to all three formulas and data obtained by the method of characteristics are in good agreement. Let us also note that the present model offers a simple physical interpretation of the angle Θ_+: 99% of the gas is expanding into a cone with a semi-angle equal to ≈3Θ_+.

EXPERIMENTAL SETUP AND PROBLEMS OF DIAGNOSTICS

The current status and history of development of the experimental base and diagnostics techniques in the field of rarefied gases at the Institute of Thermophysics SB RAS can be found in the review [5]. The first low-density wind tunnel in the IT SB RAS (labeled VS-2) with a cryocondensation pump using liquid nitrogen was developed in 1965. The capacity of this device for carbon dioxide (in molecular regime) was 25 m^3/s. The updated version, VS-3, was constructed in 1969. Its nitrogen contour provided a capacity of $1.3\cdot10^3$ m^3/s for a pressure of 0.1 Pa. Successful testing and maintenance of the VS-3 setup gave rise to wide application of cryopumps for low-density wind tunnels. Later, a setup was designed for pumping in the helium temperature range; this was called VS-4. This cryopump offered more opportunities for experiments with low-density wind tunnels. The worldwide trend in the elaboration of low-density wind tunnels initiated the development of large-scale setups VIKA and VIKING with volumes of 40 and 150 m^3, respectively. These setups had another great advantage: they could operate in an impulse mode.

Experiments reported in this paper were conducted at different stages of the VS-3, VS-4, and VIKING setups. A sketch of the VIKING setup is shown in Fig. 2. A detailed description of VIKING setup can be found in [6].

Diagnostic methods are extremely important for experiments with supersonic flows. In fact, they determine the quantity and quality of experimental information. Gas-dynamic sources also play a significant role because they provide both a required range of initial parameters for the gas (i.e. pressure, temperature, and composition) and conditions of jet formation.

Methods for the diagnostics of rarefied gas flows are varied and specific. Wherever possible (for moderate rarefaction up to 10^3 Pa), traditional tools of aerodynamics (optical methods, as well as probe methods for static and total pressure, mass velocity, enthalpy, and stagnation temperature) are used. For lower pressures, however, these methods either become useless or require corrections that sometimes exceed the measured value. The electron beam method is very valuable for investigations of rarefied gas flows. Today it has become a common method for studying rarefied gas dynamics. The key idea of the method is the analysis of processes accompanying the fast electrons passing through the gas medium. The excitation of atomic and molecular energy levels, the processes of dissociation, ionization, electron scattering on atoms and their deceleration by the Coulomb field of a nucleus lead to emission in a wide spectral range: from infrared emission to X-rays. This method has a high spatial resolution (about 1 mm^3) and it allows the density, partial concentration, transitional temperature, and the temperature of internal motion to be determined. This method provides flow visualization in cross-sections of interest. The electron beam method had been developed at IT SB RAS and now, using modern automation equipment, it has come to a good level.

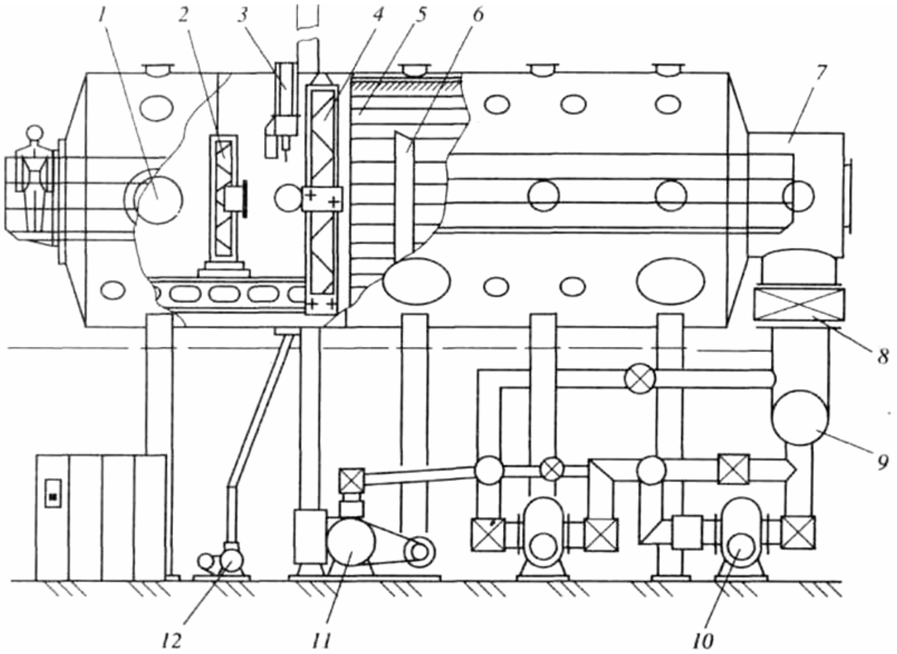


FIGURE 2. Gas-dynamic setup VIKING. 1- hatch a bayonet cover, 2 – traverse gear, 3 – electron gun, 4 – ring with the bearing sites, 5 – cryogenic evacuation system, 6 – deflector, 7- adapter, 8 – DU-1200 gate, 9 – DU-900 pipe line, 10 – rotor pumps, 11 – NVZ-500 pump, 12 – AVZ-20 unit.

This method offers wide possibilities for gas flow investigations, but it also has some restrictions. In particular, the upper limit of concentration for local measurements is about 10^{15} cm^{-3} for the visible spectral range and about 10^{16} cm^{-3} for the X-ray range. In the current work, researches by the electron beam method allowed high-accuracy measurements of local density in the field of the jet flow and visualization of the flow structure behind a single nozzle and behind nozzle blocks.

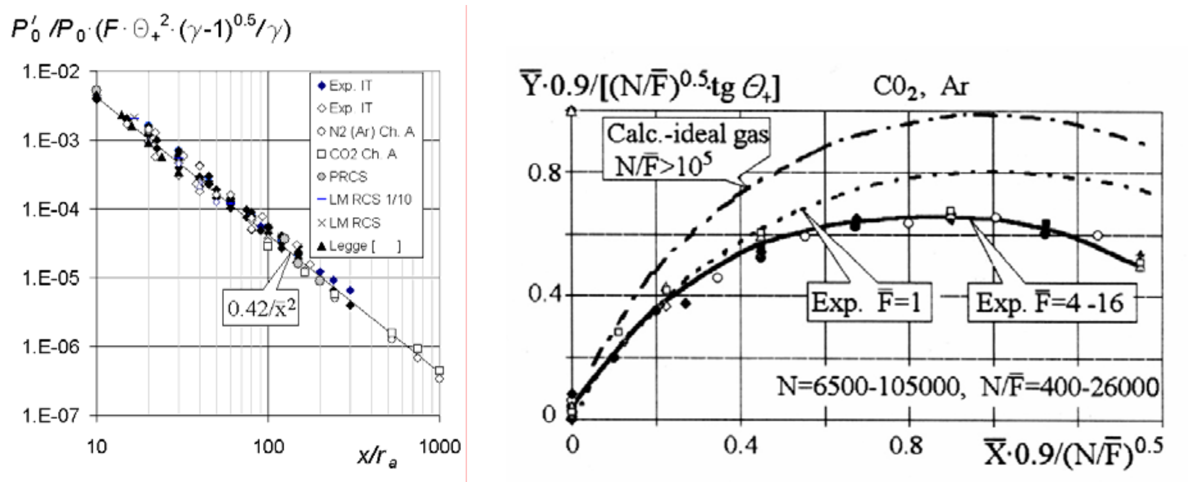
INFLUENCE OF NONEQUILIBRIUM PROCESSES ON THE FLOW IN NOZZLES AND FREE JETS, PROBLEMS OF MODELING

For understanding opportunities of mono-, di-, and triatomic gases used as model gases, a series of experimental researches was performed to study the influence of nonequilibrium processes (homogeneous condensation and vibrational relaxation) in jets of Ar, N_2, and CO_2 on the region of free supersonic expansion into vacuum and geometry of jets. It was been shown that nonequilibrium processes can render strong influence on the flow inside a supersonic nozzle and the jet behind it [1]. For argon, the basic process affecting the change in relative density is homogeneous condensation of the gas in the nozzle and in the jet behind it.

This influence can be fairly significant (for conditions of the present experiment, the relative density differs approximately by a factor of 7 from the corresponding nonisentropic values, and the Mach number decreases approximately by 2 times at the exit cross section of the nozzle). For CO_2, vibrational relaxation also affects the relative density in the jet, in addition to condensation.

With the use of the above-introduced concept of a typical angle of jet divergence Θ_+, experimental results on the distribution of total pressure in the jet (Fig. 3a) and geometry of strongly underexpanded jets (Fig. 3b) were generalized.

An important conclusion that follows from the researches performed is the possibility of controlling the distribution of parameters in jets with the help of nonequilibrium processes. Such an approach essentially expands opportunities of modeling of exhaust plumes in vacuum chambers.



(a) (b)

FIGURE 3. Generalization of experimental data on the total pressure distribution (a) and jet geometry (b)

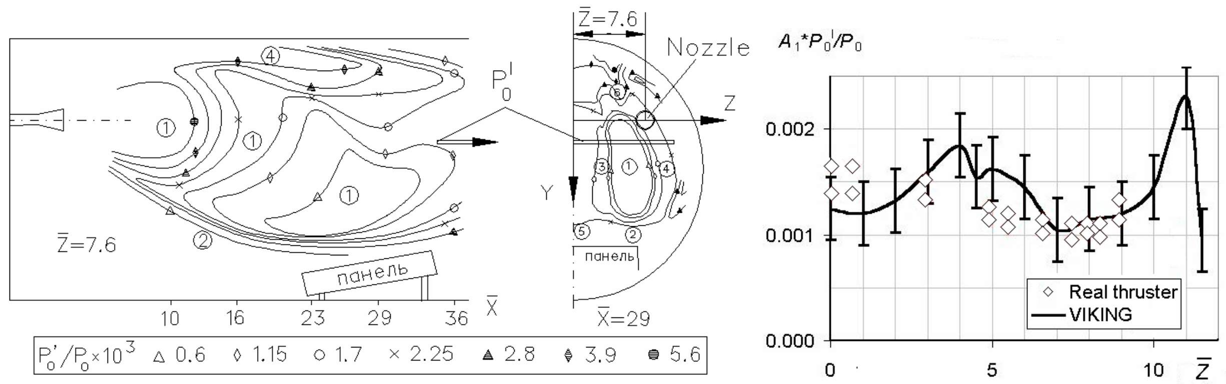
INVESTIGATION OF BLOCK JETS

Examples of applied researches are experiments where the conditions of testing of real two-nozzle thrusters real of the system for separation of the stages of the "Energia-Buran" system (thrust ~$15\cdot10^4$ N), which were performed in a vacuum chamber with a volume of 10^4 m^3, were reproduced on a 1:50-scaled model in the VIKING setup.

In model researches, the real value of the specific angle of the jet field Θ_+=30˚ was reproduced with the use of CO_2. Conditions of expansion in terms of *N* were reproduced by equating the values of the parameter $N/\overline{F}$ for real and model researches.

The wave structure of the flow field formed inside the setup and the distribution of dynamic pressure P_0^I measured by a Pitot tube (Fig. 4) were obtained in model experiments.

The data shown in Fig. 4b illustrate good correlation of P_0^I values measured in tests of real engines with the data obtained in model researches.



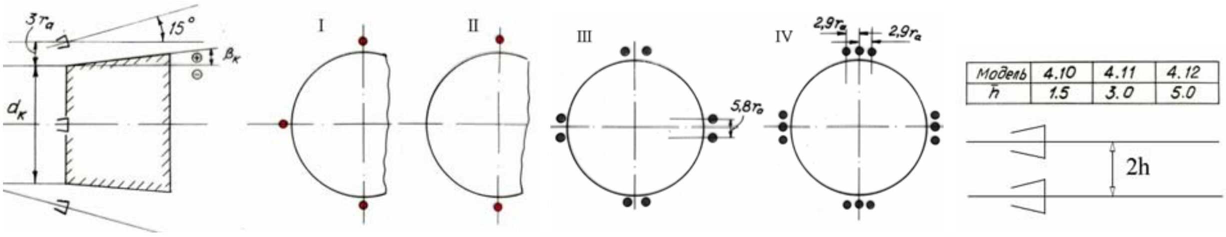
(a) (b)

FIGURE 4. (a) - Structure of jet flow field inside the setup, (b) - Comparison of results of real tests and model experiments on measurement of dynamic pressure along the lines $\overline{X}$ =34, $\overline{Y}$ =2.

A cycle of researches of the flow structure of block jets, including modeling of Shuttle thruster operation, was performed.

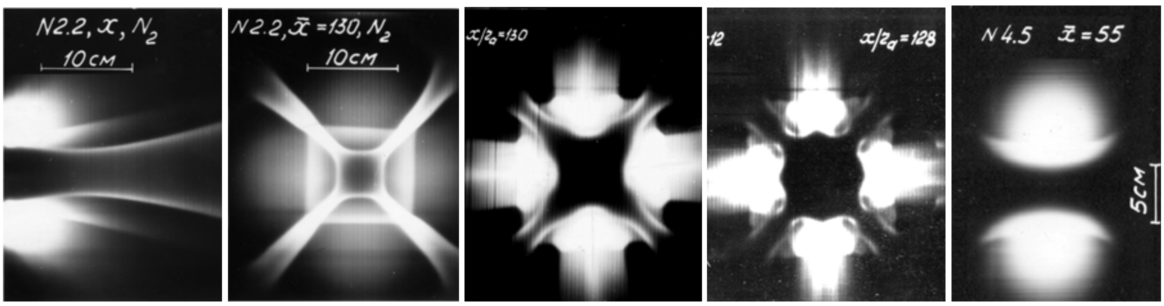
The models are schematically shown in Figs. 5 and 8a. The flow structure was visualized with the use of the electron beam method, and the distributions of local density were measured in jets behind nozzle blocks [7]. Electron beam visualization of the flow structure in longitudinal and transversal planes behind a block of four nozzles (Figs. 6a and 6b) and in transversal planes for blocks of 8, 12, and 2 nozzles (Figs. 6c, 6d, and 6e) is shown as an example.

The electron-beam method gives a clear idea about the flow structure: regions of free expansion and also shock waves arising owing to interaction of jets with the central body [8] or among themselves (Fig. 6). The gas density measured in cross sections of the jet field in planes passing through the axes of the opposite nozzles is shown in Fig. 7. The quantitative information on the flow structure (isochors) allows calculating the force and thermal influence of exhaust plumes on structural elements of the space vehicle.



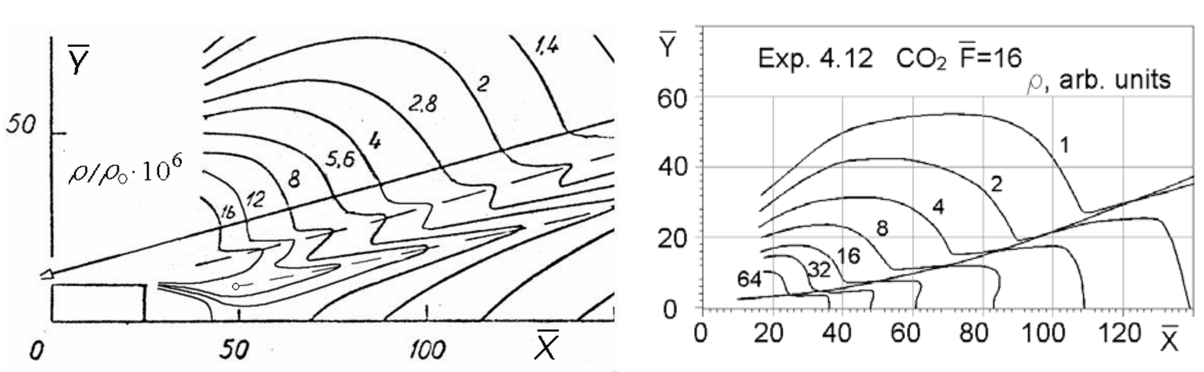
(a) (b)

FIGURE 5. Schemes of models: (a) nozzles mounted near the space vehicle body; (b) “compact” nozzles block



(a) (b) (c) (d) (e)

FIGURE 6. Results of jet field visualization by the electron beam method.

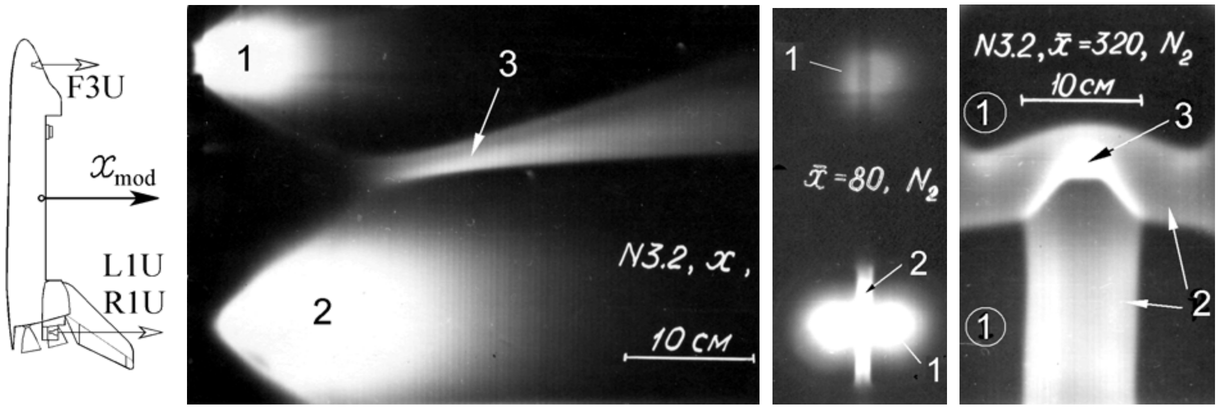


(a) (b)

FIGURE 7. Isochors in the plane Z=0: (a) experiment with scheme I in Fig. 5a; (b) experiment 4.12.

Results of jet field visualization for activation of three Shuttle thrusters are shown in Fig. 8 in the longitudinal plane (Fig.8b) and in cross sections (Figs. 8c and 8d). The flow field here contains zones of interaction of two or three jets with high levels of gas density.

Based on the experimental gas density results, the effect of jets issued by Shuttle on the MIR space station and ISS elements was preliminary quantified.



(a) (b) (c) (d)

FIGURE 8. Experiments with the 1:140-scaled Shuttle model. Flow field structure for activation of the Shuttle thrusters F3U+L1U+R1U (NORM-Z mode): 1 – free jet zone, 2 – zone of interaction of two jets, 3 – zone of interaction of three jets.

MODELING OF PROCESSES OF EXTERNAL CONTAMINATION OF THE INTERNATIONAL SPACE STATION BY JETS OF ORIENTATION THRUSTERS

Operation of various systems and devices at orbital stations, such as orientation thrusters (OT) and refueling systems, is accompanied by periodic exhaustion of liquid propellant components into space. According to experiments at the MIR Orbital Station, at OT operation, burnt and unburnt fuel fractions, including droplets (contaminants), are ejected almost into a full sphere: from 0 to 180° relative to the jet axis. This is primarily caused by specific features of gas and liquid flows into vacuum.

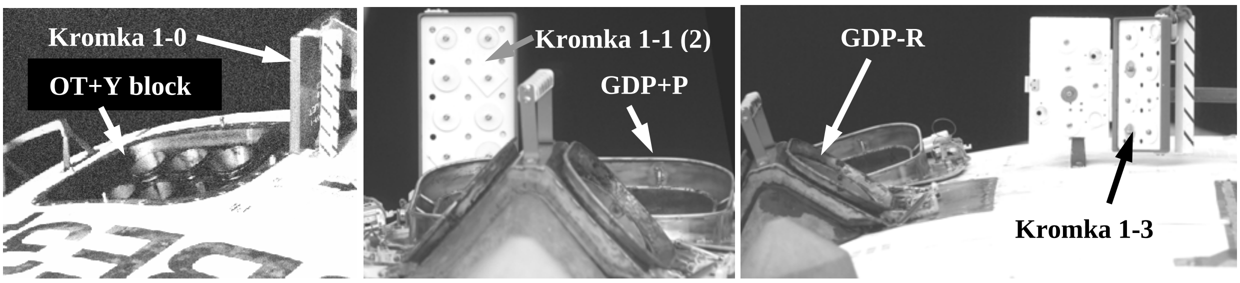
Structural elements of the orbital station that appear in the flow field of the exhaust plume are subjected to mechanical and physicochemical influence, and this is undoubtedly an adverse factor. In addition, there is a risk of contaminant penetration into the station on astronaut suits after their spacewalks. Much attention is currently paid to the problem of International Space Station contamination.

Problems of modeling of external contamination processes on the International Space Station by jets of its orientation thrusters are considered in detail in [9]. It was shown in experiments that the situation can be improved by mounting even one screen at the exit edge of the nozzle: the half-angle of liquid phase scattering decreases from 140° to about 55°.

After experimental and theoretical investigations [9], recommendations and proposals on the scheme and main geometrical sizes of gas-dynamic protecting devices (GDP) mounted on blocks of orientation thrusters of the ISS Service module were developed.

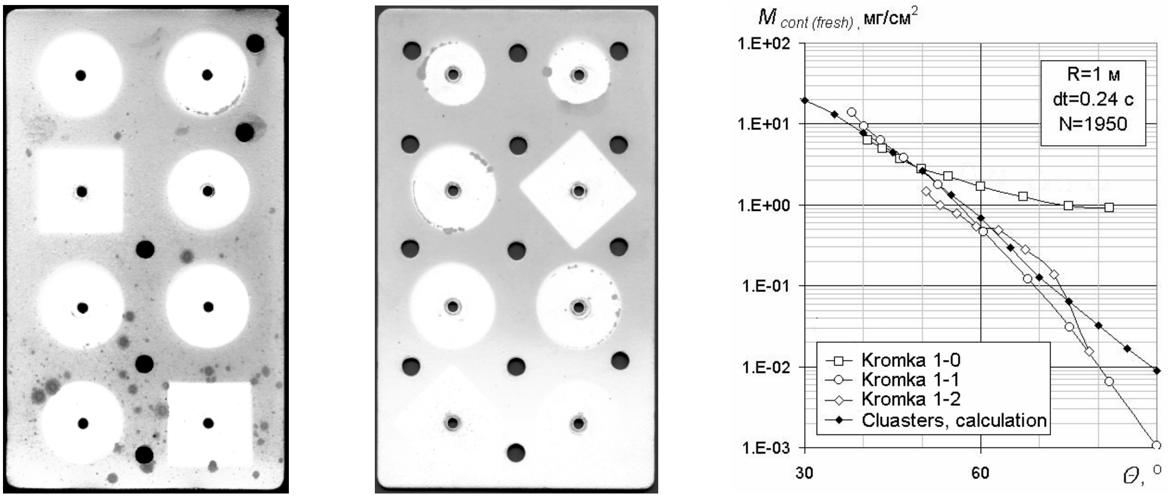
In January 2002, these gas-dynamic protecting devices were installed in all blocks of orientation thrusters at the Service Module of ISS by astronauts (Yu. Onufrienko and D. Bursch) during their spacewalk.

Within the framework of the real space experiment «Kromka 1» (Fig. 9), the efficiency of the mounted gas-dynamic protecting devices was evaluated [10]. These researches showed that these protecting devices are highly efficient (Fig. 10) and confirmed the results of model experiments.



(a) (b) (c)

FIGURE 9. Mounting of pads in the space experiment «Kromka 1»: «Kromka 1-0» - near blocks OT+Y without GDP (a), «Kromka 1-1 (1-2)» - near GDP of OT+P blocks (b), «Kromka 1-3» near OT-R block with GDP (c).



(a) (b) (c)

FIGURE 10. Contamination of «Kromka 1» pads before (a) and after (b) GDP mounting. Function of the angular distribution of PIC ejections before and after GDP mounting (c). Results of the space experiment «Kromka 1».

CONCLUSIONS

The results of joint researches of the Korolev Rocket and Space Corporation Energia and the Kutateladze Institute of Thermophysics SB RAS on vacuum-chamber modeling of plumes of orientation and control thrusters of space vehicles and space stations give a general idea on the direction and methodology of researches. Development of new approaches to statement of researches, vacuum setups, and methods of diagnostics of rarefied gas flows allowed obtaining new results on the gas-dynamic structure of jets under nonequilibrium conditions and solving a number of problems for particular space programs.

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