Modeling of Processes of External Contamination of International Space Station by Jets of Orientation Thrusters

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Abstract. The results of experimental simulation in vacuum chamber of processes of International Space Station surface contamination by plumes of orientation thrusters are reported. It was shown that the mounting of the gas-dynamic protectors on the orientation thruster allows essential reduction of the droplet (contaminating) phase backflow. Results of study of the gas-dynamic protector efficiency under the real conditions are given.

Keywords: International Space Station, orientation thrusters, exhaust plumes, contamination, modeling
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INTRODUCTION

Operation of various systems and devices at orbital stations such as orientation thrusters (OT) and systems of refueling is accompanied by periodic exhaustion of liquid propellant components into space. According to experiments at the Orbital Station MIR, at OT operation ejection of burnt and unburnt fuel fractions, including the droplet ones (contaminants), occurs into almost a full sphere: from 0 to 180° relative to the jet axis. This is firstly caused by peculiarities of gas and liquid flows into vacuum. Construction elements of the orbital station which get into the flow field of exhaust plume are undergone to mechanical and physical-chemical effect and this is undoubtedly a negative factor. Besides there is a risk of contaminant penetration into the station on astronaut suits after their spacewalks. Now great attention is paid to the problem of International Space Station (ISS) contamination.

Perhaps the radical solution is to refuse from OT using chemical fuel and transition to different-type engines, for instance, electrical ones using neutral gases with a large molecular mass: xenon, krypton, argon, fullerene C_{60} etc. But in this case the problem of electric-physical effect of the plume on orbital station elements stays in force.

Moreover at the modern stage of space technology development it is reasonable to raise a question about a decrease (exclusion, in the limit case) in a negative effect of OT plume on the station construction elements. It can be reached by limitation in the scattering angle of contaminating fractions. The technical solution of this approach is installation of special screens – gas-dynamic protectors (GDP) on the OT outlet. The installed GDP should not change the OT parameters, first of all the thrust vector and value (specific impulse). As the authors know, previously the idea of GDP use for limitation of contaminant opening angle and station pollution has not been considered.

Since propellant components used in OT are toxic, a possibility to investigate the problem of contamination by real OT in the vacuum chambers is restricted. In this case model investigations can provide valuable information of the problem of orbital station contamination. The current paper deals with preparation, development and result analysis of modeling the processes of ISS contamination by OT operation.

The most complete information on the flow structure in the plume of orientation thruster and contamination effects is presented in experimental research [1,2] performed in the vacuum chamber with helium cryogenic pump. The liquid rocket thrusters (LRT) of a low thrust (from 5 to 66 N) were studied in these papers, and extensive data on the flow structure of the plume including the droplet phase were obtained. Small (2.5 μm), large (10-20 μm) and very large (100-500 μm) drops were observed in the flow field, the latter were observed at the end of launching. Despite terms “small”, “large” and “very large” are conditional it is necessary to note that the largest drops were observed near the nozzle outlet, and they were formed due to disruption of the near-wall film used for cooling of the nozzle wall. Another important result from [1,2] is that droplets formed by disruption of the near-wall film scatter at the angles higher than 90° relative to the jet axis, i.e., they form the backflow.

Some interesting data on mechanisms of transfer and spatial distribution of condensed contaminants behind the LRT of a low thrust were obtained in [3]. According to these investigations the main part of contaminants is formed during the thruster start and stop stages. The droplet size of incomplete combustion products (ICP) in the central and peripheral areas of the plume are determined as 1 – 100 μm, and 90 % of ICP mass is carried-out by droplets of 20 – 40 μm [3].

PREPARATION OF INVESTIGATIONS AND PROBLEMS OF MODELING

From the point of problem statement, this is an outflow of the near-wall liquid film with a co-current gas flow from a supersonic nozzle into vacuum. Certainly, we consider only approximate modeling, even a real OT is tested in the vacuum chamber. The problem becomes more complex, when model liquids are used instead of the propellant components. It is very difficult to represent in model experiment the real thickness of film at the nozzle edge, its composition and temperature, and parameters of the high-temperature gas flow of combustion products. Nevertheless, even approximated modeling at possibly close representation of determining parameters allows obtaining information on the flow structure and first of all, on the liquid-droplet phase.

Film parameters at the outlet nozzle cross-section (its thickness δ_l and average velocity V_l or thickness δ_l and the value of shearing stress τ at the gas-liquid interface) can be taken as the main criteria of near-wall film modeling. Values δ_l and V_l can be calculated if the second flow rate of liquid m and shearing stress τ at the interface are known [4]:

$$\delta_\mathrm{L} = \sqrt{\frac{m\mu_L}{\pi R \rho_\mathrm{L} \tau_W}}, \quad V_\mathrm{L} = \sqrt{\frac{m\tau_W}{4\pi R \rho_\mathrm{L} \mu_\mathrm{L}}}. \tag{1}$$

Another important condition for full-scale modeling is the choice of the main parameters of the supersonic nozzle: geometry, Mach number, gas type, its temperature and flow rate, and stagnation pressure. This work takes the idea of modeling by the typical angle of jet divergence Θ, determined via a relative jet impulse $\bar{J}$ [4]:

$$\Theta = \mathrm{arctg}\left(\frac{1-\bar{J}}{\bar{J}}\right)^{0,5}, \qquad \bar{J} = \left(1+\frac{1}{\kappa\,\mathrm{M}_a^{\ 2}}\right)\left(1+\frac{2}{(\kappa-1)\mathrm{M}_a^{\ 2}}\right)^{-0,5}. \tag{2}$$

where $\bar{J} = J_a / G V_{\max}$, J_a, G, $V_{\max}$ are gas impulse at the nozzle exit section, flow rate and maximal gas velocity in the jet, correspondingly, M_a is the Mach number, κ is the specific heat ratio.

Now, the OT with thrust of about 140 N are installed at the Service Module (SM ISS). These thrusters operate using self-igniting components of propellant: asymmetrical dimethylhydrazine (heptyl, fuel) and nitrogen tetraoxide (amyl, oxidant). The total flow rate of propellant is about 50 g/s. According to (2), a relative jet impulse of this thruster ($\mathrm{M}_a \cong 4.3$, $\kappa = 1.24$) is $\bar{J}_\mathrm{H} = 0{,}87.$ Thus, on the assumption of modeling condition $\bar{J}_\mathrm{M} = \bar{J}_\mathrm{H}$ and using air ($\kappa = 1.4$) as the model gas, the Mach number of a model nozzle is $M_a = 2.94$, and this corresponds to the ratio of diameters of the outlet and critical nozzle cross-sections $D_a/D_* = 2$. Other parameters of the model nozzle: diameter of the critical cross-section, gas and liquid flow rates, etc., were chosen using modeling conditions for the near-wall liquid film and possibilities of experimental setup.

In experiments model liquids: ethanol and freon-11, whose physical properties are close to heptyl and amyl, were used as the model liquids instead of the real propellant components.

Together with experimental research numerical calculations of movements of droplets with the sizes of 1-100 μm inside the OT nozzles were performed. These calculations were carried out for orientation thrusters of the Service Module (SM OT) and Aerospace Transportation Vehicle (ATV OT) [4].

EXPERIMENTAL SETUP AND PROBLEMS OF DIAGNOSTICS

Experimental studies were carried out using the vacuum gas-dynamic setup VIKING of the Institute of Thermophysics SB RAS [5]. Relatively large volume of the working chamber (150 m^3) provides wide possibilities for work under the pulse modes used at model experiments with high gas flow rates which are unachievable at continuous operation. Supersonic conic and contoured nozzles were used as the model ones.

The construction scheme of the nozzle with a ring near-wall supply of liquid into the stagnation chamber is shown in Fig. 1. The liquid is fed through stagnation chamber detail *2* into a ring gap formed by bush *1* and nozzle *3*. The size of this gap was 0.1 mm, gap length (extension along the axis) was 7 mm, and area of the ring gap was 8.2 mm^2. At fabrication and assembling specific attention was paid to supporting of a uniform gap over the radius. One or two screens can be mounted at the outlet part of nozzles. Due to screw joints these screens could travel at different distances or angles α_1 and α_2 relative to the nozzle edge and each other. The curvature radiuses of the outlet screen edges were 0.1-0.2 mm, inner surfaces of the screens were polished.

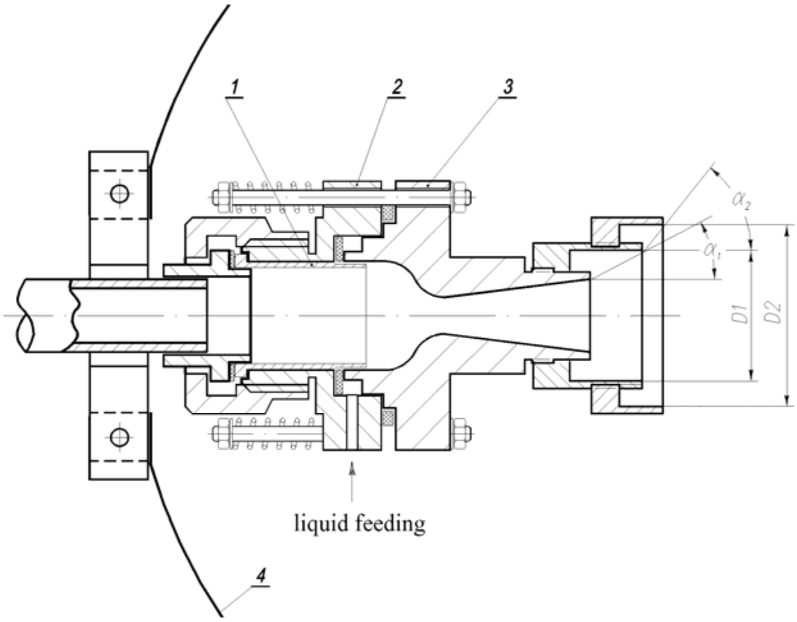

FIGURE 1. Scheme of model nozzle.

Let's consider the problems of diagnostics for the gas-droplet flows ejected into vacuum. As it was already mentioned emission of contaminating fractions (ICP) from OT into space is almost spherical. Therefore one of demands to diagnostics of these flows is to obtain simultaneously spatial distribution of the droplet phase in the whole flow field. Another problem is caused by a significant (by several orders) angular change of concentrations at flowing into vacuum both in gas and droplet phases. According to analysis the method of droplet deposition on substrates located at some radius from the nozzle outlet is the most appropriate. Narrow paper or film stripes (to exclude flow disturbances) fixed on radial corbels *4* (see Fig. 1) at the distance of 140 mm from the center of outlet nozzle cross-section were used as the substrates. Since ethanol (the model liquid in these experiments) is colorless and, moreover, it fast evaporates, the amount of droplet phase on the substrate was determined by the amount of dye (solid residue), stayed after evaporation. Rhodamine 6gKDM, which is not sublimated in vacuum, was used as the dye. The mass concentration of dye was 0.065 %, and it could hardly effect physical properties of the model liquid. After the experiment these stripes were taken from the vacuum chamber and treated using a scanner and microdensitometer.

Spatial distribution of the liquid phase in the required range of angles was also measured by the quartz sensor with high sensitivity and possibility to perform measurements in vacuum and in any spatial position. Measurement principle is based on a change in frequency of surface oscillations of a quartz plate in generator circuit depending on a mass, deposited on the plate. Together with angular distribution of the droplet phase the flow structure was visualized and density of the gas-carrier was measured using the electron-beam method.

EXPERIMENTAL RESULTS AND ANALYSIS

General structure of the droplet phase flow

According to experimental researches the general structure of the droplet phase flow arising upon supersonic ejection of a gas from a supersonic nozzle into vacuum with a near-wall liquid film (Fig. 2) was obtained.

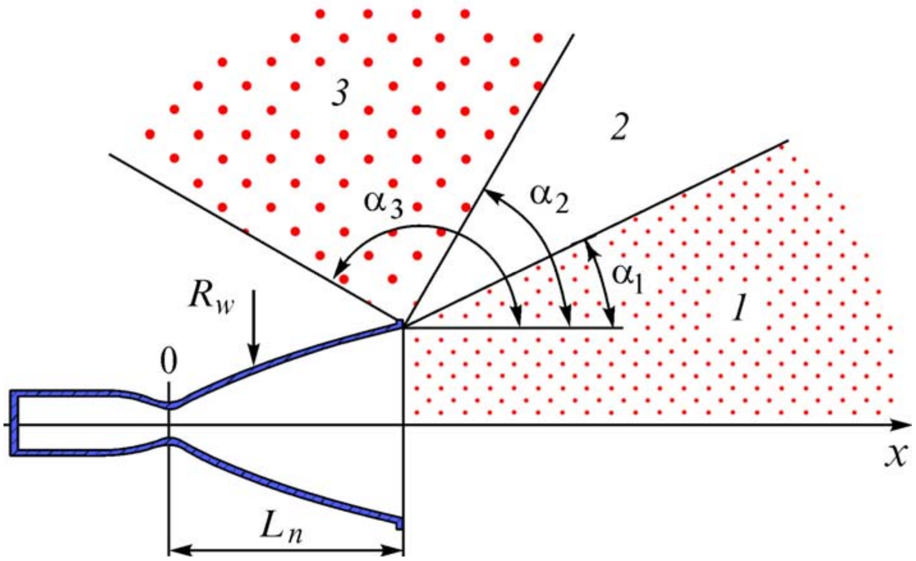

FIGURE 2. General structure of the droplet phase flow.

Two characteristic regions of the droplet phase flow (central *1* and peripheral *3*) are observed. Region *1* is caused by droplet shedding from the film surface near the nozzle throat, and their subsequent fragmentation and acceleration in the gas flow inside the nozzle and in the jet behind it. Region *3* is formed by disintegration of the near-wall liquid film on the exit edge of the nozzle, where the pressure drastically increases and the liquid becomes overheated. The process of disintegration is complicated and is caused by interaction of inertial, viscous, surface, gas-dynamic, and other forces. It is obvious that a competition of these forces is caused by the influence of the basic physical properties of the liquid (saturated vapor pressure, evaporation heat, surface tension, and viscosity), parameters of the co-current gas flow (relative velocity, nozzle shape, pressure, and temperature), and the shape of the nozzle exit edge. In region *2,* either the gaseous or the gas-cluster structure of the flow is observed.

Gas-Dynamic Protecting Devices

Schemes and designs of protectors can be different; they depend on several factors. Their main qualifying standards are as follows: low weight, reliable operation in open space and no effect on engine towing performance. Besides, it is necessary to consider design limitations on engine nozzles and their assembling at the spacecraft [6].

It was shown in experiments with GDP for SM OT that mounting of one screen at the outlet edge of the nozzle radically improves the situation: the scattering semi-angle of the liquid phase decreases from 140 to 65°, i.e., by two orders in comparison with the nozzle without a screen (Fig. 3). According to experiments, in comparison with the first screen, mounting of the second one does not provide such a result. However, the second (outer) screen is required for catching of droplets from the first screen and screening (forming of an angle) of the flow, which may occur at evaporation of propellant components from the intrascreen space between launchings of OT.

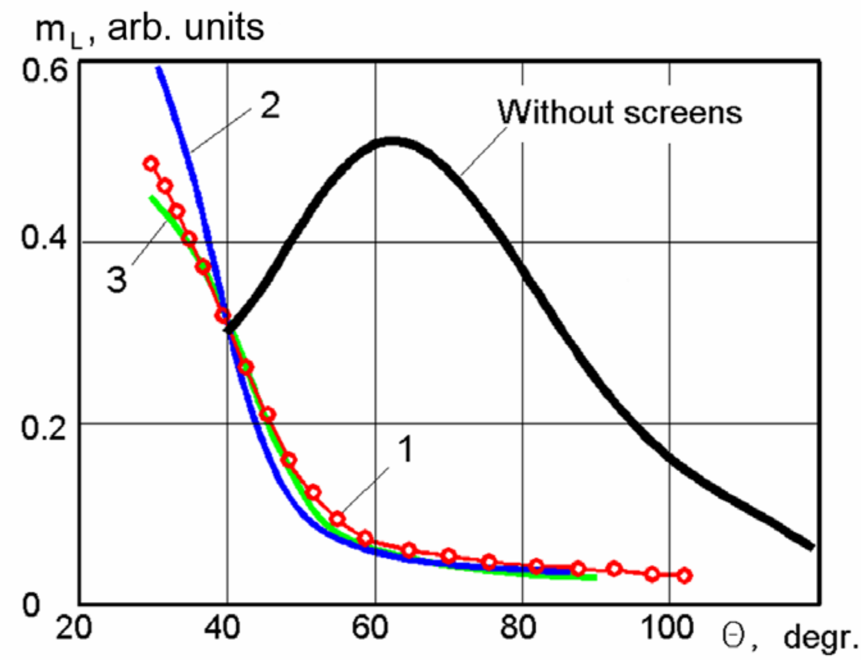

FIGURE 3. Influence of screen on spatial distribution of droplet phase. *1* - α_1=30° (single screen), *2* - α_1/α_2 = 30°/30°, *3* - α_1/α_2 = 30°/45° (double screen).

Real condition experiment «Kromka»

Since the middle of 2001, the works in the framework of space experiment "Kromka 1" were started at the ISS. One of the main goals is studying efficiency of GDP operation installed at the SM OT under real conditions. Two experimental stages have been implemented. During the first one, characteristics of ICP ejection, accumulated at the control elements of the "Kromka 1-0" pad during 3 months near the block of SM OT without GDP, were studied. During the second experimental stage, GDP was installed at the SM near OT, and the "Kromka 1-1" pad was exposed during 7 months.

The one-type pads installed near orientation thrusters of SM during spacewalk were used for this experiment. These pads consisted of a cassette in the form of an open box with the sizes of 235×140×20 mm.

After landing the weight parameter of ICP deposits on the control plate were determined under the laboratory conditions. Information on spatial distributions of ICP was obtained via computer treatment of scanned images of the plates. Data for "Kromka 1-0" и "Kromka 1-1" in cross-section Z = 66 mm are compared in Fig. 4 [7]. Results obtained along Z = 92 mm line passing over the clear areas of the plate (in experiment covered by samples of materials) are presented in the same figure. This data demonstrates the level of zero (background) intensity of coloring for the given measurements (J_0 = 0.023 – 0.027 conventional units).

These results allow estimate of operation efficiency of protectors installed on SM OT and comparison of corresponding data obtained by the field and model investigations [4].

Due to analysis of data presented we can made a general conclusion that results of the field and model experiments correlate well. For instance, it is clear that at operation of OT without GDP (experiment "Kromka 1-0") numerous traces of ICP drops are observed (see Fig. 6, *a*), at treatment these traces provide local "peaks" (see Fig. 4). At operation of OT with GDP (experiment "Kromka 1-1"), there were no drop traces on the control plate surface, and this explains smoother intensity profiles and absence of local "peaks" (see Fig. 4).

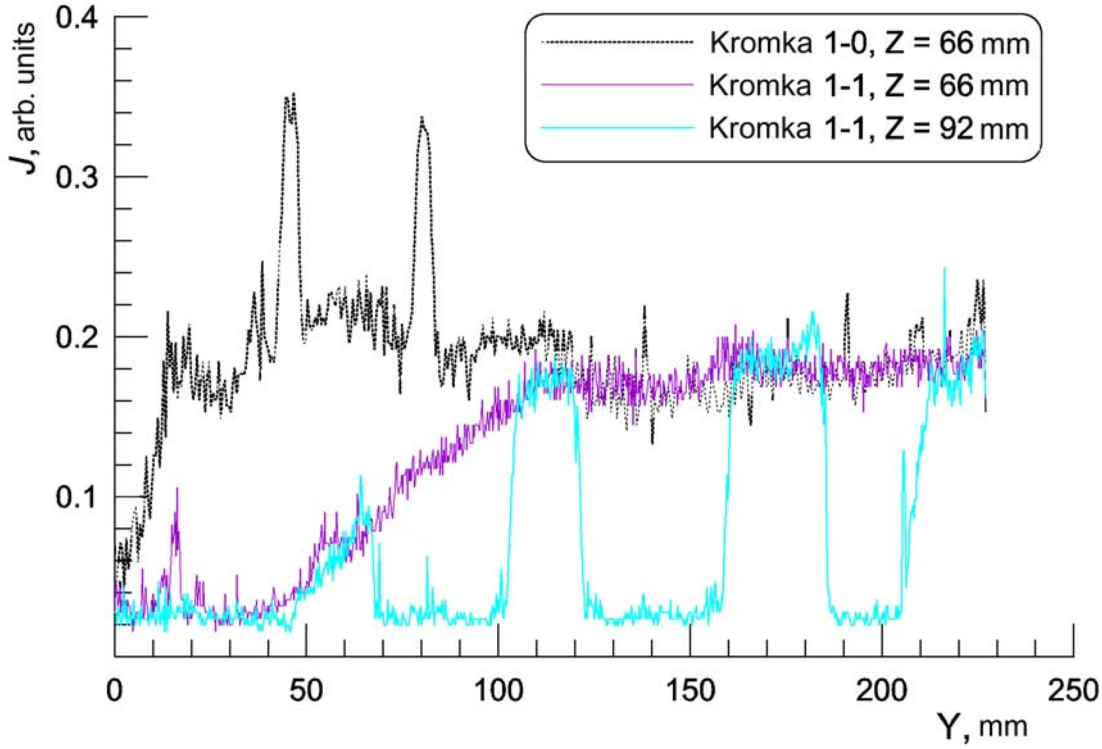

FIGURE 4. General structure of the droplet phase flow.

CONCLUSION

Development of recommendations and suggestions for the scheme and main geometrical parameters of GDP for mounting at SM OT is the main result of investigations. Further, on the basis of these recommendations, the GDP were developed and in January 2002 these GDP were mounted on OT of the Service Module of ISS by astronauts Yu. Onufrienko and D. Bursch during their spacewalk.

Investigation results on operation efficiency of GDP under real conditions have shown their good correlation with data of model experiments.

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