Model and on-orbit study of the International space station contamination processes by jets of its orientation thrusters

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Abstract. The main objective of this paper is to describe the current state of research for the problem of the International Space Station contamination by plumes of its orientation thrusters. Results of experiments carried out at the Institute of Thermophysics SB RAS modeling space vehicles orientation thruster’s plumes are presented and experimental setup is discussed. A novel approach to reduction of contamination by thrusters with the help of special gas-dynamic protective devices mounted at the exit part of the nozzle is suggested. The description and results of on-orbit experiment at the International Space Station are given. Results show good agreement for model and on-orbit experiments validating our approach.

1. Introduction
Space stations are complex systems that have many components and a variety of on-board devices. On the one hand these devices are necessary for operation and on the other one some of them can cause undesirable effects. A case in point is liquid-propellant rockets of low thrust which are used for control of space station orientation. Their operation can lead to such negative phenomena as contamination of the station external surfaces by jets.

Currently liquid-propellant rocket engines of low thrust, employing self-igniting components – dinitrogen tetroxide (amyl) and unsymmetrical dimethylhydrazine (UDMH) are used as orientation thrusters (OT) of the International Space Station (ISS). During operation of the thruster its combustion chamber is subjected to high temperatures (about 3000 K) and high pressures (about (6-10)⋅10⁵ Pa). To protect chamber walls from harmful effect of high temperatures liquid film of one of propellant components is fed on the chamber walls. Operation of these thrusters is accompanied by ejection of burnt and unburnt propellant fractions (molecular clusters and droplets) into space. Results of both model and on-orbit experiments show that incomplete combustion products (ICP) scatter almost in all the directions: from 0 to 180° relative to the jet axis. This is caused by special character of gas and liquid outflow into vacuum. The flow of gas at angles over 90° is known as backflow. Such flows lead to contamination of the external surface of the ISS and outside equipment. This in turn poses a risk of toxic ICP penetration into the living space of the ISS. Therefore minimization of contamination is important and challenging problem.

Arguably experimental studies carried out in 1983-1988 at the Hamburg technical university [1-
2] were one of the first attempts to investigate contamination effects of thruster plumes. Monopropellant and bipropellant thrusters (thrust from 5 to 66 N) were tested in a vacuum chamber, and extensive data on the flow structure of the plume including the droplet phase were obtained. Experimental data includes droplets sizes and scattering angles. It was shown that scattering angles can well exceed 90°. However the problem of OT plumes negative impact minimization on space vehicles construction elements was not considered in these studies.

During 1993-1996 experimental studies of ICP ejection from the Russian bipropellant thruster 11D428A-16 were carried out in the vacuum chamber of the Keldysh Research Center [3]. Pulse duration in these experiments was 25-50 ms. Since build-up time of the thruster is about 35 ms, the results obtained included only ejection of droplet fraction of ICP. At the same time considerable ejection of droplets from a nozzle into peripheral part of a jet was demonstrated. Dependence of angular distribution of droplets mass in near-axial and peripheral zones of a jet up to polar angle equal to 90° was obtained in those studies.

For the first time the problem of spacecraft contamination by jets of OT attracted attention at the space station MIR. Contamination of different areas near thrusters was observed during on-orbit experiment “Dvicon” carried out in 1998. However, the attention was focused on this problem only at the International Space Station.

In this paper we study the problem of spacecraft and space station contamination by jets of OT. First we describe model experiments carried out at the Institute of Thermophysics SB RAS in which approaches to ISS contamination minimization with gas-dynamic protecting devices were evaluated. Then we describe on-orbit experiments on the efficiency of gas-dynamic protecting devices carried out at the ISS by Rocket and Space Corporation ENERGIA.

2. Model experiments
The objective of the model experiments was to study the processes of backflow contamination of spacecraft surfaces by thruster jets with a fuel film used for cooling the inner surface of the nozzle, and to suggest approach for minimizing contamination. Special attention was paid to behavior of droplets into which the liquid is decomposed at the initial stage of droplet motion and to the interaction of droplets with a freely expanding gas jet.

Model experiments were carried out at the VIKING facility of Vacuum gas-dynamic complex of the Institute of Thermophysics SB RAS [4]. This experimental facility with a 150 m³ working chamber provides wide opportunities for conducting experiments in pulse and continuous modes. Since propellant components used in OT (unsymmetrical dimethyldrazine and dinitrogen tetroxide) are toxic, possibility for investigation of the problem of contamination by real OT in the vacuum chambers is limited. In this case model investigations can provide valuable information on the problem of space station contamination. In model experiments correct choice of nozzle geometry is of outermost importance. In our work we used integral approach to modeling that can reproduce typical angle of jet divergence [5]. Supersonic nozzle with geometrical Mach number M=3 (throat diameter – 10 mm, exit cross-section diameter – 20 mm) was used as a model nozzle, ethanol – as working liquid (physical properties of ethanol and UDMH, such as viscosity, saturated vapor pressure, surface tension, heat of evaporation are rather close), and purified air – as working gas.

Study of the problem considered requires diagnostics of near-wall liquid film parameters inside the nozzle, first of all its thickness. For these measurements we used technique of capacity-type probes [6], mounted near the nozzle edge (Fig. 1). Since reliability of our data is highly dependent on precision of our measurements in our experiments we paid a lot of attention to calibration of capacity-type probes. We employed plugs made of dielectric. They were tightly inserted into the nozzle and had the gap of the given depth over the probe filled with liquid (Fig. 2). This method allowed us to obtain calibration curves for each probe taking into account its individual sensitivity and position concerning nozzle surface.
Typical results of ethanol film thickness measurement depending on Reynolds number of co-current gas flow are given in Fig. 3. One can see that thickness strongly depends on parameters of gas flow – film thickness decreases from 300 to 10 microns with increase of gas Reynolds number from $10^4$ up to $4 \times 10^5$. Liquid film velocity was measured with the help of capacity technique. Velocity also depends on parameters of gas flow and is about 1 m/s. It was shown that detachment of droplets from film surface inside nozzle takes place.

Measurements of liquid film parameters in a nozzle helped us to understand mechanism of the film disintegration at the nozzle edge. In order to study gas-droplet flow which is formed behind a nozzle exit cross-section under disintegration of near-wall liquid film we measured angular distribution of droplet phase. The main challenge in carrying out these measurements was fast evaporation of droplets in vacuum.

To overcome this challenge we added special dye into model liquid. We chose a non sublimating in vacuum dye. In this approach the quantity of liquid phase was determined by the amount of remaining dye (the dry residue) on the sensor after liquid evaporation. Droplet phase angular distribution was measured with the help of spectrophotometry technique. The basic idea of this technique consists in using methods of spectral photometry for determining the amount of dye (solid residue) remaining on the sensors, mounted around the nozzle (Fig. 4), after evaporation of droplets incoming onto the sensor.
by co-current gas flow. The peripheral one \(3\) is formed by disintegration of near-wall liquid film at the nozzle exit edge.

![Figure 5: Droplet phase angular distribution](image)

![Figure 6: General structure of droplet phase](image)

One of the ways to reduce back flows of droplets is to use special protective devices (screens) mounted on the exit part of a nozzle (Fig. 7). Schematic and constructive solutions of gas-dynamic protective devices (GDP) can vary and depend on a number of factors. The basic requirements for such devices – small weight, reliable operation under conditions of outer space, absence of influence on thrust characteristics of the rocket thruster. Besides, it is necessary to consider constructive restrictions on nozzles of thrusters, their configuration on the space vehicle and also space vehicle life-span. We show [7] that the correct choice of GDP is crucially important since incorrect one may cause increase in backflows instead of reduction (Fig. 8).

![Figure 7. Gas-dynamic protective device (screen) on the model nozzle](image)

![Figure 8. Dependence of gas backflows on the angle of screen installation.](image)

3. On-orbit experiments

Based on the promising results of our model experiments protective devices for ISS were developed and manufactured by Korolev Rocket and Space Corporation ENERGIA. In 2002 they were delivered at ISS and mounted at ZVEZDA Service Module. By that time first stage of on-orbit experiment “Kromka” was completed. Its objective was to evaluate contamination of ISS surface without GDP to use as a reference for the next stages of experiment. These stages took place in 2002-2006 and allowed to come to important conclusions.

The main goal of on-orbit experiments was to evaluate GPD efficiency under long-term exposure of control plates in a zone of ICP ejection from orientation thrusters. Control plates were equipped with samples of different materials and covered with different coatings (Fig. 9). Preliminary results of on-orbit experiment were obtained by control plates photographs analysis made by crew through ISS
viewports or during spacewalk sessions. Final results of on-orbit experiment were obtained after control plates had been returned from orbit to Earth and analyzed at the laboratory [8].

Figure 9. On-orbit experiment «Kromka»

Exposure of control plates was carried out before (stage "Kromka 1-0") and after GDP installation at OT blocks (stages "Kromka 1-1", "Kromka 1-2", "Kromka 1-3") [9]. Results of on-orbit experiment confirmed efficiency of GDP for jet peripheral part shielding from ejection of the ICP droplet fraction (Fig. 10).

Figure 10. On-orbit experiment «Kromka»: contamination of control plates

An important result of on-orbit experiment was angular distributions of ICP ejected from OT of the ISS Service Module without GDP and after its installation (Fig. 11). Distributions were obtained with the help of control plates densitometry and quantitative estimations after chemical analyses of fresh (M_{cont(fresh)} – in ICP container) and dry (M_{dry} – on control plate) ICP contaminants [9]. These results demonstrate quantitative characteristic of ICP efficiency, namely the fact that in a peripheral
part of the flow at $\theta = 90^\circ$ the intensity of ICP contaminants decreased almost by 3 orders of magnitude [9]. This fact is in good agreement with results of model experiments we carried out earlier.

![Graph](image)

**Figure 11.** On-orbit experiment «Kromka»: distribution on contaminants

4. Conclusion

Our experiments have shown that operation of liquid rocket engines of low thrust that are used as orientation thrusters of spacecrafts is accompanied by ejection of incomplete combustion products. These products which scatter practically in all the directions from 0 to 180° are the main cause of both external surface of spacecraft and technical equipment contamination.

A novel approach for protection of surfaces and scientific equipment from contaminants is suggested. Design of accumulative type gas-dynamic protection devices mounted near blocks of thrusters nozzles for variety of spacecrafts is developed. The model studies evaluating efficiency of different schemes of the developed protective devices were carried out.

Results of on-orbit experiments that validate our designs and demonstrate remarkable shielding characteristics (reduction by several orders of magnitude) of protective devices installed at the International space station are presented. These results are in excellent qualitative agreement with results of our earlier model experiments validating both experimental techniques and supporting GDP as a valid approach for solving the problem of spacecraft contamination by orientation thrusters.

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References

[1] H. Trinks 1987 *AIAA Paper* 87-1607
[2] H. Trinks, I. Kaelsch 1987 *AIAA Paper* 87-1603
[3] S. Rebrow, Y. Gerasimov 2001 *AIAA Paper* 2001-2818
[4] V.G. Prikhodko, G.A. Khramov, V.N. Yarygin 1996 *Instrum. Exp. Tech.* 39 309-311
[5] V. Yarygin, Yu. Gerasimov, A. Krylov, V. Prikhodko, and I. Yarygin 2011 *Microgravity Sci. Technol.* 23 15-23
[6] A.F. Serov, S.V. Kotov, A.D. Nazarov et al. 1997 *Instrum. Exp. Tech.* 40 136-139
[7] V.N. Yarygin, V.G. Prikhodko, P.A. Skovorodko, I.V. Yarygin 2016 *Thermophys. Aeromech.* 23 937-940
[8] Yu.I. Gerasimov, A.N. Krylov, S.P. Sokolova et al. 2003 *Thermophys. Aeromech.* 10 555-565
[9] Yu.I. Gerasimov, V.N. Yarygin 2016 *Phys.-Chem. Kinetics Gas Dynam.* 17(4) (in russian)