Gas dynamic protective devices for orientation thruster jets of space vehicles and orbital stations

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Abstract. Here is a brief review of model and on-orbit experiments on the problem of contamination of spacecraft and orbital station external surfaces, including the International Space Station, by jets of orientation thrusters.

1. Introduction

Currently there are various approaches to control the spatial attitude of spacecrafts and orbital stations. They are usually based on the use of low-thrust liquid-propellant rocket engines that operate on self-igniting propellant. However, when they are switched on, the ejection of unburned propellant components from the thruster nozzles in the form of a droplet phase is observed. The exhaust flames of the rocket engines exert a force and thermal effect on the external surface of the spacecraft, and droplets of unburned combustion products that have reached the structural elements of the spacecraft contaminate them and cause negative chemical reactions. Moreover, they can even pose a danger to the crew if astronauts touch the contamination with a spacesuit during their spacewalk and then carry them inside the spacecraft. The most harmful are the droplets flying into the peripheral area of the jet (backflows) at an angle of more than 90 degrees relative to the nozzle axis.

For the first time, attention to the problem of the contaminating effect of orientation thruster jets was paid at the MIR space station. Within the framework of the “Dvicon” on-orbit experiment [1], carried out in 1998, the presence of contaminants in various parts of the external surfaces around orientation thrusters of the MIR station was established. But no measures were taken to solve the problem. Contamination problem became urgent at the International Space Station (ISS), where special precautions for astronauts when working outside the station near blocks of orientation thrusters were prescribed, and the special gas-dynamic protective devices for the thruster nozzles were developed. On-orbit experiments on the problem of the ISS contamination were carried out in the framework of “Kromka” experiment and continued in the “Impact” experiment [2]. Simultaneously with on-orbit studies, model experimental studies were carried out in vacuum chambers in order to understand the mechanisms of contaminating effects of spacecraft orientation control thruster jets and find out the ways to minimize them. This paper presents a brief review of studies on the problem of the ISS contamination by jets of orientation thrusters carried out at the Kutateladze Institute of Thermophysics SB RAS in collaboration with colleagues from the Korolev Rocket and Space Corporation “Energia”. The issues of modeling in vacuum chambers of spacecraft and orbital stations orientation thruster jets are discussed: the choice of modeling criteria, measurement techniques, comparison of the model and on-orbit experimental results.
2. Experimental setup and measurement technique

In our experimental modeling of the ISS contamination process by jets of orientation thrusters, we in fact investigate the joint outflow into vacuum from a supersonic nozzle of a near-wall liquid film and a gas flow. Moreover, we can only speak about approximate modeling, since we use model liquid and gas in experiments, but not the real propellant components. It is very difficult to reproduce in experiments the real composition of combustion products, temperature and film thickness inside a real engine. Nevertheless, even an approximate modeling with the fullest possible reproduction of the main parameters allows obtaining the necessary information on the flow structure, first of all, of the liquid-droplet phase.

The correct choice of modeling conditions, namely supersonic nozzle geometry, Mach number, type of gas, its temperature and flow rate or stagnation pressure is of great importance under model experiments simulating real jet of spacecraft thruster. Usually the magnitude of Mach number $M_a$ and the specific heat ratio $\gamma$ are reproduced in experiments. There are no special difficulties with reproduction of the Mach number, but it is rather problematic to reproduce real value of $\gamma$ for high-temperature combustion products in a model experiment. In this situation, it is expedient to use the integral characteristics for jet outflow into vacuum. In our studies, we suggested the concept of modeling the typical angle of jet divergence $\theta_+$, which is determined by the relative jet impulse $\bar{J}$ [2,3]:

$$\theta_+ = \arctg \left( \frac{1 - \bar{J}}{\bar{J}} \right)^{0.5},$$

$$\bar{J} = \left( \frac{J_a}{G V_{\text{max}}} \right) \left( \frac{1 + \frac{1}{\gamma M_{\text{a}}^2}}{1 + \frac{2}{(\gamma - 1) M_{\text{a}}^2}} \right)^{-0.5},$$

where $\bar{J} = J_a / G V_{\text{max}}$, $J_a$, $G$, $V_{\text{max}}$ are gas impulse at a nozzle exit cross-section, gas flow rate and maximal velocity in a jet, respectively. With this approach it is necessary to reproduce in the experiment the magnitude of the relative impulse of the rocket engine by a combination of $\gamma$ and $M_{\text{a}}$. Currently, orientation thrusters with thrust of about 140 N are installed on the Service Module of the ISS. The real value of Mach number of this thruster is $M_{\text{a}} \approx 4.3$, the specific heat ratio is $\gamma = 1.24$, and the relative jet impulse according to (2) is $\bar{J}_R = 0.87$ [2]. In these experiments, we accept the modeling criteria: $\bar{J}_M = \bar{J}_R$, and then using air ($\gamma = 1.4$) as the model gas, we obtain the Mach number of the model nozzle $M_{\text{a}} = 2.94$. It corresponds to the ratio of the radii of the exit and critical cross-sections of the nozzle $r_e/r_\ast = 2$.

Here it is pertinent to note that nonequilibrium processes accompanying supersonic gas outflow into vacuum, such as homogeneous condensation and vibrational relaxation, can have a determining influence on the typical angle of jet divergence. This is illustrated in figure 1, where the electron-beam visualization of Ar jet behind a supersonic nozzle in vacuum under condensation conditions (figure 1b) and without it (figure 1a) is shows. It can be seen that the heat of condensation supplied to the supersonic flow drastically changes the flow structure in the underexpanded jet, namely the jet transforms from the usual X-shaped configuration of the central shock behind the supersonic nozzle to the flow with the Mach disk, which is typical of underexpanded jets behind the sonic nozzle.
Figure 1. Outflow of Ar jet into vacuum from a supersonic nozzle under different gas stagnation temperatures $T_o$. a - $T_o = 640$ K, b - $T_o = 159$ K.

As for the criteria for modeling a near-wall liquid film, they can be taken as the parameters of the film in the exit cross-section of the nozzle: its thickness $\delta_{liq}$ and average velocity $V_{liq}$, or thickness $\delta_{liq}$ and the magnitude of the shearing stress $\tau$ at the gas-liquid interface. The values $\delta_{liq}$ and $V_{liq}$ can be calculated if the second liquid flow rate $m$ and the shearing stress $\tau$ at the interface are known \cite{4}:

$$m = 2\pi r \delta_{liq} \rho_{liq} V_{liq}, \quad \tau = \frac{C_f}{2} \rho V^2 = \mu_{liq} \frac{2V_{liq}}{\delta_{liq}}.$$  \hspace{1cm} (3)

Then

$$\delta_{liq} = \sqrt{\frac{m \mu_{liq}}{\pi \rho_{liq} \tau}}, \quad V_{liq} = \sqrt{\frac{m \tau}{4\pi \rho_{liq} \mu_{liq}}}.$$  \hspace{1cm} (4)

Currently, there are no data in academic literature for determining $\tau$ at the outer boundary of liquid film in the presence of a high-velocity, including supersonic, co-current gas flow. However, due to the small thickness of the near-wall liquid film, the value of the shearing stress $\tau$ on the outer surface of the film as a first approximation can be taken equal to the value of $\tau_o$ on the nozzle wall without a liquid film.

Experimental studies were carried out on a large-scale (about 150 m$^3$) vacuum setup VIKING \cite{5}. Taking into account objectives of the work the setup was additionally equipped with test sections and diagnostic tools for measuring the local parameters of the near-wall liquid film inside the nozzle and studying the structure of the flow of gas and gas-droplet flows behind the nozzle exit in vacuum. The schema of the test section is shown in figure 2. The model nozzle was installed vertically inside the vacuum chamber, and the outlet of the nozzle was directed downward. The working liquid (ethanol) was fed into the nozzle prechamber through an annular gap 0.1 mm wide. At the same time, a working gas (air) was blown through the nozzle. The experiments were carried out in a pulsed mode. The typical ejection time was 5 s, while the settling time of the ejection process was less than 1 s. The choice of ethanol as a working liquid was due to the fact that it rather accurately simulates heptyl, which is used in rocket engine both as a fuel and to create a cooling film on the nozzle wall. In the main part of the experiments, the effect of screens on the value of gas-droplet backflows was investigated. Screens (figure 2b) with angles $\alpha = 30, 45, 60, 75$ and 90° were chosen. In this case, the
ratio of the inner diameter of the screen to the diameter of the nozzle exit was the same and equal to 1.75.

![Figure 2](image)

**Figure 2.** Schema of test section. *a* – general view, *b* – nozzle with screen.

1 – nozzle, 2 – capacitive type sensors, 3 – injectors, 4 – plate diaphragm, 5 – electromagnetic valve, 6 – pressure sensor, 7 – measuring tube, 8 – control unit and data collecting system, 9 – spatial grid for paper substrates, 10 – vacuum chamber.

The following measurements were carried out in experiments using developed techniques: gas pressure in the supply line, in the nozzle prechamber, in the vacuum chamber; total and instantaneous liquid flow rates; thickness and velocity of liquid film inside the nozzle; angular distribution of droplet phase behind the nozzle exit; temperature of liquid film formed on the external surface of the nozzle; direct and back gas flows in the jet. The flow structure of droplet phase behind the nozzle exit was visualized, followed by obtaining the distribution functions of droplets on sizes, directions-of-fly and velocities.

3. **Results and discussion**

Experiments were carried out in wide ranges of flow rate both of liquid (Reynolds number $Re_{\text{liq}}$) and gas flows (Reynolds $Re_{\text{gas}}$ and Weber $We$ numbers). Much attention in experiments was paid to obtaining data on the parameters of liquid film under its interaction with co-current gas flow inside the nozzle and on the flow structure in the jet behind the supersonic nozzle under ejection into vacuum.

As an example, this flow structure is shown in figure 3. One can clearly see a turn of liquid film on the nozzle lip, its emerging to the external surface of the nozzle and rise up even against gravity. Going forward the liquid film on the external surface is partially dispersed into droplets, forming gas-droplet backflows. It was shown in experiments, that installation of closed-type screen on the exit part of the nozzle significantly reduces the backflow. Experiments also showed that the film formed on the external surface of the nozzle due to evaporation is cooled to a temperature at which the pressure of its saturated vapor becomes equal to the pressure in the surrounding space (in the vacuum chamber). More detailed information on the behavior of a used liquid film on the nozzle lip and the spatial flow structure of droplet phase behind the supersonic nozzle in vacuum can be found in [6].
Figure 3. Outflow of liquid film with co-current gas flow from a nozzle into vacuum.

The cycle of experiments on measuring pressure inside the screens, as well as direct and back flows using the Pitot tube in order to understand the role of a co-current gas flow, its spatial flow structure and the effect of screens on the magnitude of backflows was carried out. The corresponding results of measurements and calculations on the effect of the geometric parameters of the screens (angle $\alpha$) on the value of backflows are shown in figure 4 [7]. The most interesting and important result of these measurements is the conclusion that not every screen reduces the backflow, and unsuccessful choice of the screen (in this case, when $\alpha = 30^\circ$) leads even to gas backflow increase as compared with an outflow from the nozzle without screen. This is caused, apparently, with an increase in the boundary layer inside the long screen (with $\alpha = 30^\circ$).

Figure 4. Effect of the screen on gas backflows behind supersonic nozzle.

Another series of measurements using the Pitot tube concerned the obtaining of transverse profiles of the total pressure in the chosen cross-sections in the jet behind the nozzle exit, but without screens. These chosen cross-sections corresponded to the position of the exit cross-sections of the screens (with $\alpha = 30$, 45 and 60$^\circ$). In this case, the pressure in the vacuum chamber was equal to the measured pressure inside the corresponding screen. The results of measurements of transverse profiles of the total pressure in the jets behind the nozzle without a screen for three pressures $p_k$ in the vacuum chamber are shown in figure 5. It can be seen that the transverse size of the jets obtained at different chosen distances from the nozzle exit and different pressures in the vacuum chamber are approximately the same and sufficiently close to the output diameter of the screen (35 mm). From figure 5 one can also see an increase in the intensity of the oblique shock waves at higher pressures in the vacuum chamber, which is apparently due to the transition to less rarefied (more continuous) flow regimes in the mixing layer behind oblique shock waves.
From the results presented, it can be concluded that under gas outflow from the nozzle with a closed screen into rarefied medium (in the limit into vacuum), the flow inside the screen is formed in such a way that the border of the jet coincides with the screen lip (its transverse size at the exit cross-section of the screen is always equal to the screen diameter).

4. Conclusion

The suggested approaches to modeling in vacuum chambers the jets of spacecraft and orbital station orientation thrusters, the development of the experimental base and measurement techniques allowed the obtaining of sufficiently complete and reliable information on the effects of contamination by such jets, to understand the reasons for their appearance, to propose ways to minimize them, and develop recommendations for gas-dynamic protective devices (screens) for their subsequent installation on the orientation thrusters of the ISS Service module. Further, the results of studies carried out in the framework of the on-orbit experiment “Kromka” confirmed the high efficiency of the developed protecting devices, and their use allowed a significant, by the orders of magnitude, reducing in the effects of contamination by the jets of orientation thrusters.

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