Experimental study of gas jet outflow from a supersonic nozzle with a screen into vacuum

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Abstract. The flow structure formed behind supersonic nozzle with a screen under joint outflow of gas and near-wall liquid film into vacuum is studied experimentally. Pressure in cavity between the nozzle and the screen is measured. Transversal pressure profiles in a jet behind the nozzle for different values of background gas pressure in the vacuum chamber are obtained. The significant effect of the screen on droplet phase flow structure behind the nozzle is shown.

1. Introduction

Single-phase and multiphase flows behind supersonic nozzles in vacuum are of both fundamental and practical interest. A fundamental feature of the supersonic jet outflow of single-phase and multiphase medium into vacuum is a non-equilibrium nature of physicochemical processes (homogeneous and heterogeneous condensation, vibrational relaxation, dissociation, ionization, chemical reactions, radiation, etc.) which accompany outflow. This property stimulated the active use of jet outflow into vacuum to study nonequilibrium processes and their role in the formation of such flows [1]. In practical terms, supersonic jet outflow into vacuum is of interest for rocket and space technology, primarily for the development and manufacture of control and orientation thrusters for spacecraft and orbital stations. Currently, low-thrust liquid-propellant rocket engines are used as the control and orientation thrusters of the International Space Station, in which a fuel film is used to cool the nozzle walls [2]. Results of model and on-orbit studies show, the jets of these thrusters can be a source of contaminating flows of droplet or gas phases, which apparently leads to negative effect on the spacecraft itself and its structural elements [3]. At the present stage of space engineering technology, it is quite expedient to raise the question of reducing (in the limit – exclusion) the negative effect of orientation thruster’s jets on the elements of the space station. One of the ways is limiting the scattering angle of contaminating fractions. The technical solution to this approach is to mount special screens, gas-dynamic protective devices, on the thruster outlet. In that event the mounted protective devices should not change the parameters of the thrusters, first of all, the thrust vector and its magnitude. The idea of using screens to reduce backflow (contaminating) is not new. In particular, such screens, including those cooled by liquid nitrogen, are applied to reduce the back flows of oil vapors in high-vacuum diffusion pumps [4]. However, the idea of screens application for orientation thrusters of spacecraft is rather new. Experimental results of earlier studies carried out at the IT SB
RAS showed that the main source of contamination of spaceships under operation of orientation thrusters is backflow (at the angle of more than 90 degrees relative to the jet axis) of droplet phase. Its appearance is caused by special features of the gas outflow into vacuum, namely the fact that gas flows into almost full sphere from the source. The approach of using gas-dynamic protecting devices is proposed to reduce backflows.

Since the problem of spacecrafts contamination by jets of orientation thrusters cannot be solved purely by calculation due to its complexity, experimental studies of thruster’s plumes aimed at establishing the mechanisms and processes occurring under the jet outflow of gas from the nozzle with near-wall liquid film are relevant. This study is a continuation of the experimental research carried out at the IT SB RAS on modeling jets of the International Space Station control and orientation thrusters. The main attention is paid to the development of measurement techniques for obtaining quantitative data on the spatial distribution of droplet phase behind the nozzle exit and the screen in vacuum, as well as to study the physical mechanism of the screen, installed on the nozzle outlet, effect on the gas-droplet flow structure behind the supersonic nozzle in vacuum. It is shown that pressure in cavity between the nozzle and the screen brings the main contribution in formation of backflows. This pressure ultimately determines the flow structure of both gas and droplet phases at the lip of the supersonic nozzle and the screen as well.

2. Experimental setup and measurement technique
The experimental studies were carried out at the vacuum gas-dynamic complex of the IT SB RAS, which consist of a number of vacuum chambers and diagnostic equipment for gas and gas-droplet flows. Supersonic nozzle with Mach number M = 3 (with a conical shape of the supersonic part and a critical section diameter of 10 mm) was used in the work. Ethanol was used as the working liquid, and purified air was used as the working gas. The nozzle was mounted inside vacuum chamber with the outlet faced downwards. Experiments were carried out in pulse mode with typical time of single run $t = 10$ s. Initial pressure in vacuum chamber was set in the range from 1 up to 450 Pa. Gas flow rate in experiments varied from 5 up to 20 g/s, liquid flow rate – from 0,5 up to 2 g/s.

The diagram of the nozzle with the mounted screen is shown in figure 1. The developed design provides possibility of measuring the pressure in cavity between the screen and the nozzle through the tube 7. The cavity is sealed from the surrounding space (vacuum chamber) by gasket seals 6. To study the effects of angle $\phi$ (figure 1) on pressure in the cavity and on angular distribution of droplet phase the number of replaceable screens of various lengths was manufactured. The ratio of the inner diameter of the screen to the outlet diameter of the nozzle was chosen constant and equal to 1.75.

![Figure 1. Scheme of the nozzle with screen. 1 – gas-dynamic source body, 2 – nut, 3 – M3 screw, 4 – screen, 5 – nozzle, 6 – gaskets, 7 – tube for connecting pressure gauges, 8 – bushing](attachment:image.png)
In experiments we measured the pressure in the cavity between the nozzle and the screen under gas outflow into vacuum together with liquid film and without it, recorded the transversal pressure profile behind the nozzle exit without the screen under outflow into the background gas, and measured the angular distribution of the droplet phase behind the nozzle exit with and without the screen.

To measure the pressure in the cavity between the nozzle and the screen, the TDM2-D pressure sensor was used. The sensor output signal was recorded using AVM-4306 digital voltmeter connected to a computer. The equipment was calibrated before the experiments in stationary mode (in quite gas) at the adjusted constant pressure in the vacuum chamber, which was controlled by MKS Baratron Type 626A capacitive vacuum meter.

To record the transversal pressure profile behind the nozzle exit without the screen, the TDM2-D pressure sensor with a Pitot tube was installed on the coordinate mechanism. The coordinate mechanism made it possible to accurately set the position of the sensor relative to the nozzle exit during the experiment. The distance from the nozzle exit to the pressure sensor was set the same as the distance from the nozzle exit to the screen exit in experiments with the screen.

To measure the angular distribution of the droplet phase behind the nozzle exit with the screen and without the screen, we used the developed technique of dyed liquid droplets deposition on paper substrates [5]. Deposition on substrates allowed us to obtain with the help of spectrophotometry method the dependences of the droplets mass scattering from the nozzle lip on the angle $\phi$ relative to the jet axis.

3. Results and discussion

The effect of the installed screen on the flow structure of droplet phase in the gas-droplet jet behind the nozzle exit is exerted in a number of factors. Firstly, the screen geometrically limits droplets scattering from the nozzle lip and its external surface under disintegration of near-wall liquid film. Secondly, the screen increases the pressure on the external part of the nozzle, and this pressure affects the process of the film emerging on the external surface of the nozzle and its disintegration into droplets [6]. Dependence of the pressure $p$ in cavity between the screen and the nozzle on the angle $\phi$ of the screen installation (length) under gas outflow into vacuum with and without near-wall liquid film is shown in figure 2.

![Figure 2. Dependence of pressure in cavity between nozzle and screen on angle $\phi$](image-url)
One can see that when the screen is installed on the nozzle outlet the pressure in cavity between the nozzle and the screen in experiment significantly exceeds the pressure in the vacuum chamber. The smaller the angle of installation of the screen, the higher is this pressure. The presence of near-wall liquid film increases the pressure between the nozzle and the screen. This is caused apparently by evaporation of liquid from the external surface of the nozzle.

To understand the mechanism of the installed screen effect on the flow structure of gas and droplet phases behind the nozzle exit we carried out the experiment on the outflow of gas into the background gas from the nozzle without the screen. The background gas pressure (pressure in the vacuum chamber) was set equal to the measured pressure in cavity between the nozzle and the screen. Using a Pitot tube and pressure sensor, the pressure profile behind the nozzle exit was recorded (the distance $Y$ from the Pitot tube to the jet center was varied from -30 to +30 mm). The Pitot tube was installed at a distance from the nozzle exit equal to the distance to the corresponding screen exit. Transverse profile of the total pressure $P_o'$ at a distance $X = 15$ mm from the nozzle exit under gas flow outflow into the vacuum chamber with pressure of $P_k = 420$ Pa is shown in figure 3.

![Figure 3. Transversal pressure profile behind supersonic nozzle. $X = 15$ mm, $P_k = 420$ Pa](image)

From figure 3 one can clearly see the core of the jet (in the range of $Y$ values from -15 up to +15 mm) and shock waves (at $Y = -17.5$ mm and $Y = +17.5$ mm). The distance from one shock wave to another is 35 mm. This corresponds to the internal size of the screen, although the screen was not installed in this experiment. Similar results are obtained for other values of the background gas pressure and the corresponding distance $X$ from the nozzle exit to the Pitot tube. In other words, the geometry of the gas jet behind the nozzle under outflow into vacuum coincides (in the region from the nozzle exit cross-section to the screen exit cross-section) with the geometry of the jet behind the nozzle without the screen under outflow into background gas. The pressure in the background gas should be equal to the pressure in the cavity between the nozzle and the screen.

For practical applications, the possibility to control droplet phase backflows is of great interest. Using of gas-dynamic screens on the exit part of the nozzle is one of the ways to control backflows. The main idea is to reduce dynamic pressure of gas flow on droplets at the exit edge of the screen and, as a result, to reduce backflows of droplet phase. The experiments carried out showed the possibility of significant decrease in backflows of droplet phase. Dependence of rhodamine concentration $Q$ on the angle $\alpha$ from the jet axis behind the nozzle with the screen and without the screen is shown in figure 4.

4. Conclusion

The effect of gas-dynamic screen on gas-droplet flow structure under ejection of near-wall ethanol film accompanied by air flow from the supersonic nozzle with Mach number $M = 3$ into vacuum is investigated. It is shown that under gas outflow from the nozzles into background gas, the position of shock waves in the jet corresponds to the dimensions of the screen. This takes place when background gas pressure is equal to the pressure in cavity between the nozzle and the screen under outflow into vacuum. It is found that the screen affects the process of the liquid film scattering from the external surface of the nozzle. The possibility of using gas-dynamic screens installed on the exit part of the nozzle for droplet phase backflows control is shown.

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