Control of droplet phase angular distribution under near-wall liquid film ejection with co-current gas flow from the supersonic nozzle into a vacuum

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Abstract. Flow structure behind a supersonic nozzle under near-wall liquid film ejection with the co-current gas flow into a vacuum is studied experimentally. Quantitative measurement results on the angular distribution of the droplet phase behind supersonic nozzle are obtained using the developed spectrophotometry technique. The authors have revealed the effect of near-wall liquid film parameters (Reynolds number of the film) and co-current gas flow parameters (Reynolds number of gas flow) on the formation of droplet phase backflows. The capability of controlling the droplet phase backflows, using the screens installed on the nozzle exit has been shown as well.

1. Introduction
Currently, near-wall flows of liquid films, including flows accompanied by gas flow, are widely used in various apparatuses and devices, for example, nozzles cooling of liquid propellant rocket engines, including thrusters of spacecraft and orbital stations. Gas dynamics of the multiphase medium is the subject of numerous theoretical and experimental studies [1-2]. Gas-liquid flows are prominent among these studies, including in particular problems, such as droplet dispersion, their interaction with the gas flow, physical processes at the interface, etc. However, the number of papers related to flows of liquids and gas-liquid mixtures into a vacuum is limited. The interest in this problem, apart from pure space applications (water discharge [3], purging of the space station refueling pipes [4]), is associated also with several technological applications [5-6].

In our earlier studies, we found [7] that a complicated spatial flow structure of the droplet phase is formed behind the nozzle under ejection into a vacuum. This structure includes the central and peripheral flow regions. The special feature of such flows is the formation of droplet phase backflows (at angles over 90 degrees relative to the jet axis). The occurrence of these backflows can cause contamination of surfaces near the thrusters. This is a negative factor, taking place, for example, under the operation of the spacecraft control and orientation thrusters. The objective of this work is to investigate experimentally the possibilities of controlling the angular distribution of droplets behind the nozzle to minimize backflows. Based on the conducted experimental studies, the influence of the determining parameters of the near-wall liquid film and the gas flow on the angular distribution of the droplet phase behind the nozzle exit, as well as the possibility to control the flow structure of droplet phase using gas-dynamic screens is shown.
2. Experimental setup and measurement technique

The experimental studies were carried out at the vacuum gas-dynamic complex of the IT SB RAS, which consists of several vacuum chambers and diagnostic equipment for gas and gas-droplet flows. A supersonic nozzle with a Mach number $M = 4$ (with a conical shape of the supersonic part and a critical section diameter of 10 mm) was used in the work. Ethanol colored with Rhodamine 6G xanthene dye (dye concentration was equal to 0.5 g per 1 liter of ethanol) was used as the working liquid, and the air was used as the working gas. The liquid was fed to the nozzle stagnation chamber from the container outside the vacuum chamber through a pipeline (4 mm in diameter) and four injectors. Air was supplied to the test section through a pipeline (8 mm in diameter) from the tank of 270 liters in volume. The air to the tank was supplied from a compressor through the filter and water separator. Flow diaphragm with a diameter ranging from 1 to 4 mm was installed at the nozzle inlet. A novel measurement technique that allows obtaining quantitative data on the angular distributions of the droplet phase behind the nozzle exit during a single run was developed in the work. The experiment was carried out as follows: the nozzle was mounted inside a vacuum chamber with the outlet faced downwards (Fig. 1), vacuum chamber was pumped down to a pressure of about 1 Pa, then the supply of working gas to the pre-chamber of the nozzle was switched on for 10 seconds, and 1 second later the liquid film was fed to the nozzle wall for 3 seconds. During the experiment, a gas-droplet flow was formed behind the nozzle exit, and droplets of colored liquid dispersed from the nozzle lip onto paper substrates, which were installed at a distance of $R = 75$ mm, leaving traces on them. The gas flow rate in experiments varied from 2 up to 22 g/s, liquid flow rate – from 0.6 up to 1.8 g/s.

![Figure 1. Scheme of the test section.](image1)

1 – spherical frame for fixing paper substrates, 2 – supersonic nozzle.

Paper substrates after the experiment were removed from the vacuum chamber and subjected to further processing using the spectrophotometry technique. Detailed information regarding spectrophotometry of substrates is presented in [8]. As a result the quantitative data on the angular distribution of the dye depending on the angle $\varphi$ relative to the jet axis, and distribution of droplet phase in the gas-droplet flow behind the nozzle exit as well as its outlet were obtained.
3. Results and discussion

To determine the effect of both the near-wall liquid film parameters and gas flow parameters on measurement results, a series of experiments were carried out in which the flow rate of the liquid supplied into the nozzle and the gas flow rate varied. In experiments where the parameters (Reynolds number) of the near-wall film were changed, three flow rates of liquid \( G_{\text{liq}} = 0.6, 1 \) and 1.8 g/s were chosen with a constant gas flow rate \( G_{\text{gas}} \), that corresponded to Reynolds numbers \( \text{Re}_{\text{liq}} = 5.1, 8.5, \) and 15.3, respectively. During each experiment, droplets were deposited on 8 paper substrates, after which the angular distribution of the dye on substrates was determined, and then the data obtained were averaged. Data on the specific distribution of the dye on substrates depending on the angle \( \phi \) for the indicated flow rates of liquid are shown in Fig. 2.

![Figure 2. The effect of liquid flow rate (Reynolds number \( \text{Re}_{\text{liq}} \) of the liquid film) on the angular distribution of the droplet phase.](image)

One can see that two typical maxima of the distribution function (the first one in the central region of the flow and another one in the peripheral region) are clearly observed for all liquid flow rates. The change in liquid flow rate (Reynolds number of the film) primarily affects the peripheral region of the flow. Namely, when the flow rate of liquid increases, the maximum is shifted to the region of larger angles, in particular, backflows of the droplet phase increase substantially at angles over 90 degrees relative to the jet axis. At the same time, the central region of the flow remains virtually unchanged.

This is because the formation of the central region of the flow is caused by droplets detachment and entrainment by gas flow from the film surface inside the nozzle. The amount of liquid entrained from the film surface depends on Weber number \([9]\), and with an increase in liquid flow rate by a factor of three at a constant gas flow rate, Weber number increases by about 1.5 times. However, the increase in liquid flow rate affects the amount of liquid on the external surface of the nozzle, causing more intense dispersion in the peripheral region of the flow. It has been found that with an increase in fluid flow from 0.6 up to 1.8 g/s, the weight ratio of the droplet phase in the central and peripheral flows \( m_c/m_p \) decreases from 0.361 down to 0.127.

In experiments on the effect of Reynolds number of co-current gas flow on the angular distribution of the droplet phase, the gas flow rate varies from 2 up to 12 g/s, which corresponds to gas flow Reynolds...
numbers ranged from $4.5 \times 10^3$ up to $3.2 \times 10^4$. Measurement results on the specific quantity of the dye on paper substrates depending on the angle $\varphi$ for different gas flow rates $G_{\text{gas}}$ are shown in Fig. 3.

![Graph of specific quantity of dye vs. angle from the jet axis](image)

**Figure 3.** The effect of gas flow rate (Reynolds number $Re_{\text{gas}}$ of gas flow) on the angular distribution of the droplet phase. $Re_{\text{liq}} = 5.3$.

One can see that the change in Reynolds number of gas flow has a significant effect on the flow of the droplet phase in the central region. Namely, as the gas flow rate increases from 2 up to 12 g/s, the Weber number in the critical cross-section of the nozzle increases from 4.7 to 16.3. Therefore, the process of droplet detachment and entrainment inside the nozzle is intensified, resulting in a fourfold increase in the maximum value of the droplet mass in the critical cross-section of the nozzle. In Fig. 3 it is also possible to see that with an increase in gas flow rate there is a slight shift (approximately from 50 to 60°) in the maximum angle of droplets ejection from the external surface of the nozzle. This appears to be due to an increase in the density of gas flow in the jet, and, as a consequence, an increase in the dynamic effect of gas flow on droplets in the peripheral flow region.

Thus, it was found that a change in liquid film Reynolds number can significantly affect the distribution of the droplet phase in the peripheral flow region behind the nozzle exit. At the same time, a change in gas flow Reynolds number can significantly affect the central flow region. For practical applications, the possibility to control droplet phase backflows is of great interest. This can be done by employing gas-dynamic screens installed on the external part of the nozzle. The basic idea of using screens is to reduce the dynamic head of gas on droplets at the exit edge of the screen and, as a result, to reduce backflows of the droplet phase. The experiments carried out showed the possibility of significant, by orders of magnitude, decrease in backflows of droplet phase (Fig. 4).
Figure 4. Angular distribution of the droplet phase behind the nozzle with screen and without the screen. Regas = 4.9·10⁴, Reₗiq = 8.1.

Conclusion
The authors investigated the effect of the determining parameters of the near-wall liquid film and concurrent gas flow on the angular distribution of the droplet phase in gas-droplet flow formed under the ejection of near-wall ethanol film accompanied by air flow from the supersonic nozzle with Mach number M = 4 into a vacuum. It has been revealed that by varying the Reynolds number of the liquid film, it is possible to control within certain limits the flow structure of droplet phase behind the nozzle exit in the peripheral region of the jet, and by varying the Reynolds number of the gas – in the axial region of the jet. The conducted experiments have shown the possibility of using gas-dynamic screens installed on the exit part of the nozzle to decrease drastically the backflows of the droplet phase without reducing the thrust characteristics of the nozzle.

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