Mach number effect on droplet phase angular distribution behind a nozzle under near-wall liquid film outflow with co-current gas flow into vacuum

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Abstract. The paper is devoted to experimental study of near-wall ethanol film outflow with high-velocity co-current air flow from sonic and supersonic nozzles into vacuum. Using the developed measurement techniques (droplet phase flow structure visualization, deposition of droplets on paper substrates, spectrophotometry method), the effect of the nozzle Mach number on angular distribution of droplet phase in the central and the peripheral flow regions behind the nozzle exit is established.

1. Introduction
The outflow of liquids and gas-liquid mixtures into vacuum from channels of different geometry is of both scientific and practical interest. The study of physical processes and phenomena accompanying liquid outflow into vacuum: instant boiling, dispersion into droplets, phase transitions on the surface and inside droplets, interaction of droplets with supersonic gas flow, etc. is of fundamental importance. For practical applications, the outflow of liquid into vacuum is of interest, in particular, for space technologies from the point of view of spacecraft surfaces contamination under operation of drainage devices, control and orientation thrusters, refueling systems, etc. Despite the fact that the jet outflow of a gas into vacuum has been the subject of numerous experimental and theoretical studies, the problem of the joint outflow of a gas flow with a liquid, in particular with near-wall film, is studied insufficiently. The main feature of the problem is the "overheating" of the working liquid when under ejection into vacuum (saturated vapor pressure of liquid is several orders of magnitude higher than the pressure in the vacuum chamber even at room temperature), which leads to its explosive disintegration into droplets at the nozzle lip.

Currently there are few publications on the outflow of water into vacuum [1-3]. Almost all of them are related to space applications and devoted to ejection of water from orbital stations through cylindrical channels of different diameters. It is shown in these papers that the jet of water under outflow into vacuum breaks up into droplets, which quickly freeze due to cooling because of the high value of specific heat of evaporation. At the same time, we have not found publications on the study of water and other liquids outflow into vacuum in the form of near-wall film with a co-current gas flow.
A number of experimental studies devoted to solving the problem of the International Space Station (ISS) external contamination by jets of orientation thrusters, in which a fuel film is used the nozzle walls cooling [4-5], was carried out earlier at the Kutateladze Institute of Thermophysics SB RAS (IT SB RAS). Ethanol was used in these experiments as a working liquid, which by its main physical properties (density, saturated vapor pressure, specific heat of evaporation, viscosity, surface tension coefficient), is close to asymmetrical dimethylhydrazine, currently used as fuel component for the ISS orientation thrusters. It was found that under the liquid film outflow into vacuum, the near-wall liquid film, moving along the internal surface of the nozzle, not only disintegrates into droplets at the nozzle lip, but also emerges to the external surface of the nozzle and begins to move along it in the opposite direction, even against gravity.

Studies of the effect of the geometrical parameters of the nozzle (primarily the Mach number), as well as the parameters of the co-current gas flow (Reynolds and Weber numbers) and the near-wall liquid film (Reynolds number of the film), both on their interaction inside the nozzle and on the formation of two-phase gas-droplet flow behind the nozzle exit in vacuum are of special interest. The main attention in this study is paid to investigation of the nozzle Mach number effect on the spatial distribution of droplet phase in gas-droplet flow behind the nozzle exit under outflow into vacuum.

2. Experimental setup and measurement technique

We used the vacuum gas-dynamic complex of the IT SB RAS, which includes the number of vacuum chambers and diagnostic equipment for gas and gas-droplet flows. Two nozzles with identical subsonic part ($D = 20$ mm in diameter), throat ($d = 10$ mm in diameter) and length ($l = 25$ mm) but different exit part were used in experiments: sonic nozzle (Mach number $M = 1$) with cylindrical exit part and supersonic nozzle ($M = 4$) with a conical shape of supersonic part. Ethanol colored with Rhodamine 6G xanthane dye (dye concentration was equal 0.5 g per 1 liter of ethanol) was used as working liquid, and air was used as working gas. The technique of droplet deposition on paper substrates which allows one to obtain quantitative data on the angular distributions of droplet phase behind the nozzle exit during a single run was used. Measurement technique description as well as experiment details could be found in the paper [6]. Initial pressure in vacuum chamber was about 1 Pa. Experiments were carried out in pulse mode. Droplets of liquid scattered from the nozzle lip onto paper substrates, installed at a distance of $R = 75$ mm, and lefted traces on them (figure 1). Reynolds number of gas flow varied in experiments from $8 \times 10^3$ up to $5.5 \times 10^4$, Reynolds number of liquid film – from $8.2$ up to $15.5$.

![Figure 1. Scheme of test section.](image)
3. Results and discussion
The typical view of paper substrates after the experiment is shown in figure 2 for sonic and supersonic nozzles.

![Figure 2. Paper substrates after experiment.](image)

One can see that two typical coloring regions are observed on the substrates: the central region and in peripheral one. At the same time, the coloring character in the central region is rather uniform for each nozzle, while in the peripheral region traces of separated droplets of different sizes appear. In this case, larger (single) droplets are observed for the nozzle with $M = 4$ and their appearance and deposition is, apparently, probabilistic. Measurement results on the substrates coloring intensity are shown in figure 3.

![Figure 3. Dependence of coloring intensity $I$ on angle $\varphi$.](image)

One can clearly see difference in the formation of droplet phase spatial flow structure behind sonic and supersonic nozzles, both in the dimensions of droplets, and in the sizes of the central and
peripheral flow regions. It should be noted that the results shown in figure 2 and 3 are of a purely qualitative nature and give only a general idea on the dimensions and distribution of the droplet phase behind these nozzles. The technique described in [6] is applied for quantitative measurements. To obtain more reliable flow pattern, the processing results are averaged over 8 substrates in each experiment. The angular distributions of droplet phase behind the nozzle exit cross-sections, obtained with the help of paper substrates spectrophotometry, are shown in figure 4 for both sonic and supersonic nozzles.

![Figure 4. Dependence of dye quantity Q on angle φ.](image)

From figure 4 it is possible to see that the flow structure of droplet phase for both nozzles is qualitatively similar: there are two typical flow regions (central and peripheral), but nevertheless significant differences are observed. First, the central region for the sonic nozzle is wider, it is limited by angles $\varphi = 0-50^\circ$ versus $\varphi = 0-35^\circ$ degrees for the supersonic nozzle. This result is expected, since the central region is formed due to droplets detachment from near-wall liquid film surface inside the nozzle. The intensity of droplets detachment depends on Weber number, which is maximal inside the nozzle in its critical cross-section. In the supersonic nozzle Weber number decreases sharply, but in the sonic nozzle Weber number stays almost constant behind the critical cross-section. It leads to more intensive detachment of droplets from the film surface and entrainment by gas flow. Second, the position of the maximum in the peripheral region of the flow is different as well: for the sonic nozzle it is located near $\varphi = 85^\circ$, while for supersonic nozzle near $\varphi = 50^\circ$. This is connected to the fact that the peripheral region is formed at the nozzle lip both due to the “phase explosion” of the near-wall film reaching the nozzle exit and due to interaction of scattered droplets with co-current gas, which is flowing around nozzle lip in the Prandtl-Meyer expansion fan. In that event the angle of jet expansion into vacuum behind the sonic nozzle significantly exceeds the angle behind the supersonic nozzle. Thus it is apparently to assume that the effect of Mach number on spatial flow structure of droplet phase under joint outflow of near-wall liquid film with co-current gas flow from the nozzle into vacuum takes place mainly the peripheral region of the flow: the higher the Mach of the nozzle, the narrower gas-droplet jet behind the nozzle becomes. However, droplet phase backflows is likely to appear for any Mach numbers.
4. Conclusion
The effect of Mach number on the flow structure of droplet phase in gas-droplet flow behind a nozzle exit under outflow of near-wall ethanol film with co-current air flow into vacuum is studied experimentally. It is found that for the nozzles used with Mach numbers $M = 1$ and $4$, despite the similar general structure of the flow of the droplet phase (formation of two typical flow regions, central and peripheral), significant differences are observed as well. A wider central flow region is formed behind the sonic nozzle in comparison with the supersonic one. This is due to more intensive detachment of droplets from the surface of near-wall liquid film inside the sonic nozzle below its critical section. The maximum of the angular distribution function for the droplet phase in the peripheral region of the flow behind the sonic nozzle takes place at larger angles than behind the supersonic nozzle. This is due to the special features of droplets interaction with gas flow behind the nozzle, namely the maximum position depends on the limiting angle of jet expansion at the nozzle lip in vacuum. The results obtained can be used in practical applications for developing theoretical models of the considered flows.

References
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