Features of formation of a fluid flow flowing into a highly rarefied medium through a capillary

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Abstract. Experimental results of investigation of the form and structure of the flow of ethanol and propylene glycol into a highly rarefied medium (vacuum) through a capillary are presented. It is shown that when liquid flows vertically along gravity into a vacuum with a pressure of residual gases significantly less than the pressure of saturated vapors at the outlet temperature, the liquid jet, in contrast to the flow into a dense gas medium, is statistically unstable, subject to bending deformations and explosive spray.

1. Introduction

In the programs of space exploration and development, considerable attention is paid to small and micro-sized satellites which allow solving a large number of scientific and applied problems [1]. Currently used small satellites are not equipped with propulsion systems for orbital correction, which limits their life due to orbital decay. Equipping miniature satellites with micro-nozzle engines for orbit correction is promising. One possible solution to this problem is the use of fluid sprayed into outer space to obtain traction [2]. The flow of fluid from the nozzles is used in the relative positioning systems of miniature satellites relative to each other [3]. Liquid expiration from nozzles is also used in spacecraft jet cooling systems [4].

A necessary element in the development of such engines is ground-based simulation of the outflow of gas-liquid flows from nozzles and channels into the rarefied atmosphere of various compositions in the vacuum installations.

When the liquid flows into a vacuum, in contrast to the flow into a dense gas medium [5], there is no force interaction of the jet with the surrounding gas, which perturbs the flow and leads to atomization of the jet. The absence of force interaction allows us to study the influence of surface tension and evaporation processes on the flow of thin jets. In particular, the discharge into a medium with a pressure lower than the pressure of saturated liquid vapors (superheated liquid) may be accompanied by boiling [6-7], jet breaks, and other effects. The mechanisms of fluid flow from nozzles or long channels into the medium at atmospheric pressure or slight rarefaction have been studied for a long time and in detail [5, 8-9].

The purpose of this work is to study the flow of liquids through a thin capillary into a highly rarefied environment (outer space, highly rarefied atmospheres of planets) with a controlled degree of rarefaction. The studies were carried out with low-viscosity ethanol, which has a high vapor pressure at the test temperatures, and viscous propylene glycol, which has a low saturated vapor pressure at the test temperatures.
2. Experimental setup
The research was carried out at the gas-dynamic stand LEMPUS-2 of Novosibirsk state University [10]. The schematic diagram of measurements is shown in Figure 1. The stand evacuation system (2) provided a high vacuum (up to 0.1 mPa) of residual gas in the expansion chamber with a diameter of 700 mm and a length of 1200 mm in the absence of a liquid jet. Observation and photographing of continuously flowing microjets of the investigated liquids were carried out through an optical window (10) within the observation section from the nozzle to the chamber wall with a length of up to 400 mm. The studied liquids were flowing out of the heated nozzle (11). The capillary was connected by a polyamide tube to a vessel with the test liquid (8) located outside the vacuum unit. The temperature of the liquid $T$ in the vessel and the heated nozzle were controlled by digital resistance thermometers (6) and (4) with an error of 0.1 K. The pressure drop $\Delta P_0$ was determined as the difference between the pressure $P_0$ over the liquid measured by the pressure gauge (7) in the vessel and the residual pressure $P_h$ in the vacuum chamber measured by the vacuum meter (3). For comparison with the data at atmospheric pressure, the vacuum chamber was filled with air, and the pressure in the liquid vessel was created by the compressor (5). To implement liquid flow modes at pressure drops less than 100 kPa, the vessel (8) was connected to a vacuum pumping system.

![Figure 1. Experimental setup diagram.](image)

The studies were carried out in the vertical (along the force of gravity) direction of the flow of ethanol micro-jets (96%) and propylene glycol (99.7%).

3. Experimental results
We studied a continuous steady flow of liquid from a capillary (cylindrical nozzle) with an elongation $l/d = 63$ made of stainless steel with a polished outer surface of length $L = 25.1$ mm, outer diameter $d = 0.65$ mm, and hole diameter $d_h = 0.40$ mm. The parameters of the modes for ethanol studied in this work are given in table 1. The values of the surface tension coefficient $\sigma$ and the dynamic viscosity coefficient $\mu$, and the saturated vapor pressure $P_s$ of ethanol are taken from [11]. Parameter $N = \Delta P_0/P_h$ is the ratio of the pressure drop on the capillary to the pressure in the vacuum chamber during liquid outflow; and $N_s = P_s/P_h$ is the degree of expansion of the saturated steam.
Table 1. Experimental modes of ethanol flow depending on the heating temperature of the nozzle $T$.

| Number of mode | $T$ (K) | $\sigma$ (mPa·m) | $\mu$ (mPa·s) | $P_s$ (kPa) | $\Delta P_{0}=100$ (kPa) | $\Delta P_{0}=20$ (kPa) |
|---------------|--------|------------------|---------------|------------|-----------------|-------------------|
| 1             | 295    | 22               | 1.16          | 5.81       | 100000          | 1                 |
| 2             | 295    | 22               | 1.16          | 5.81       | 600             | 170               |
| 3             | 295    | 22               | 1.16          | 5.81       | 2.2             | 45000             |
| 4             | 317    | 20               | 0.78          | 21.2       | 2.2             | 45000             |
| 5             | 323    | 19.5             | 0.7           | 28.5       | 2.6             | 38000             |
| 6             | 335    | 18.4             | 0.57          | 50.9       | 2.6             | 38000             |
| 7             | 344    | 17.6             | 0.51          | 77.5       | 2.6             | 38000             |
| 8             | 353    | 16.8             | 0.47          | 116.8      | 2.6             | 38000             |

Photos of ethanol jets for modes 1-3 (table 1) are shown in figure 2. When the pressure drop at the nozzle was $\Delta P_0 = 100$ kPa (figure 2a - 2c), the ethanol jet flowed out of the nozzle at a speed of 7.2 m/s, when the pressure drop was $\Delta P_0 = 20$ kPa (figure 2d-2f), the flow rate was 1.4 m/s.

A jet of ethanol outflowing from the capillary located at the top of the image into a dense medium with a back pressure of 100 kPa (figure 2a, 2d) generally has three parts: "compact", in the photo is seen as dark, "fragmented" (in the photo it looks light), which turns into a "sprayed" area at the bottom of the image. The "compact" part of the ethanol jet that flows out of the capillary at a pressure drop of 20 kPa has a length of up to 40 mm, while the length of the similar part in the jet that flows out of the capillary at a pressure drop of 100 kPa is 64 mm. It should be noted that these data do not agree with [5]. In this work, it is stated that when the pressure drop increases 5 times, the length of the "compact" part of the jet should grow proportionally, whereas in our measurements, the length of the part increased about 1.5 times.

In a jet of ethanol outflowing into a rarefied medium with a residual pressure $P_h = 600$ Pa (figures 2b, 2e), the sprayed area is not seen. The jet in these modes is subject to bending deformations that increase with a decrease in the pressure drop on the capillary. In a jet of ethanol flowing into a vacuum...
(figures 2c, 2f), bending deformations increase, but the marked tendency to increase the strain of the jet with a decrease in the pressure drop on the nozzle persists.

![Figure 3](image3.png)

**Figure 3.** Sampling of observed alcohol flows from the capillary in mode 3. \( \Delta P_0 = 100 \text{ kPa} \).

![Figure 4](image4.png)

**Figure 4.** Sampling of observed alcohol flows from the capillary in mode 3. \( \Delta P_0 = 20 \text{ kPa} \).

It should be noted that the length of the "compact" part of the jet with a decrease in the back pressure of the medium decreases regardless of the pressure drop on the nozzle. The peculiarity of the outflow into vacuum was the presence of a "sprayed" part of the jet with a cone of spray of 12 \( \div \) 16\(^\circ\), which at a low pressure drop on the capillary was formed directly from the "compact" part. When the pressure drop on the capillary is 100 kPa, the "sprayed" part is preceded by a "fragmented" part of the jet. The cone of separation of particles at this difference is less than that at 20 kPa. A drop of alcohol in various stages of formation was observed on the outer surface of the capillary near its exit section. At the end of the formation, the drop slides to the exit cross section capillary and breaks away from the it.

The marked features of the modes shown in figure 2 relate to the selected quasi-stationary outflow periods. An important feature of the flow of liquid into a vacuum was the strong instability of the jets.
Figures 3 and 4 show photos illustrating some of the observed forms of instability of the ethanol jet at various arbitrary time mode 3 in table 1. The brightness and contrast of the photos were intentionally increased for better visualizing the details. You can see the arbitrary change of both the direction and the nature of the flow, and explosive spray of the jet is observed. All jets with pronounced "compact" and "fragmented" parts are curved. Bending deformations, as can be seen from figure 4, may increase with a decrease in the pressure drop on the capillary. So, in figure 4b, the jet has an s-shape. The jet in the output section of capillary is sprayed partially in figure 3c and completely in figure 3d. The angle spray is approximately 80-85°. In the sprayed jet in figure 3d the rod structure is visible near the section of the nozzle, similar to that observed on short conical nozzles when isooctane outflows into a vacuum [13,14].

As can be seen from figures 3c, 3d, a drop with a diameter of approximately 5dₐ lifts along the nozzle against gravity to a height of up to 10dₐ. An even more significant lift of the drop along the capillary was observed with a small pressure drop on the capillary. A similar flow of liquid along the outer surface of the nozzle was observed in [8].

Propylene glycol has a high viscosity [12] in the temperature range of 295 – 360 K, so its outflow into the atmosphere with a pressure of 100 kPa and into the vacuum in the temperature range of 295 – 330 K at the studied pressure differences on the capillary turned out to be mainly droplet one. The transition to an unstable jet, similar to that for ethanol, was observed at temperatures above 340 K and a pressure drop at the capillary of 100 kPa. Explosive propylene glycol spraying was not observed in the studied temperature and pressure range.

Periodic structures and bending deformations of the jet stream are probably associated with symmetric and asymmetric capillary waves of a large period [5]. Special points in the jets were also found, after which the flow direction changed sharply. This may be due to phase transitions (boiling, freezing of the liquid). However, discussion of these and some other processes goes beyond the limited scope of this presentation.

Conclusion
Studies have shown that when the liquid outflows along the gravity force from a long capillary into a vacuum, jets of ethanol at temperatures above 290 K, and jets of polypropylene glycol above 340 K are curved. Ethanol jets are often instantly sprayed in form a vapor-gas jet. However, the construction of models of the processes occurring in such jets is still to be done in the future.

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