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Features of inviscid fluid microjets outflow into vacuum

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The paper presents experimental results on ethanol microjets outflow from a capillary (vertical flow by gravity) and from a hole in the wall (horizontal flow). The long-term liquid microjet flowing into vacuum has been shown to be highly unstable with sudden changes in direction, structure and observable density and essentially differing from well-studied modes of outflow into the atmosphere as well as from the modes of short-term outflow into vacuum. The main specific features of the flows and conditions giving rise to instabilities are described. Possible explanation of the reasons for microjet destruction is given.

Keywords: liquid microjet, barocapillary instability of flows, modeling of vacuum conditions, ethanol.

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The cosmic space as a low-pressure medium provides technological opportunities based on the effect of instantaneous liquid evaporation. In the open space, this ensures unique characteristics and advantages of position control systems [1], fuel feed systems [2], cooling and temperature control systems [3].One of the possible solutions in designing attitude and approach-correction engines for mini- and microsatellites of the new generation of the CubeSat format [4,5] is the thrust creation using liquid sprayed from the nozzle. The liquid discharge into the rare medium (vacuum) is accompanied by a number of peculiarities absent in dense media. The absence of aerodynamic drag of gas surrounding the jet in the dense medium excludes the force interaction between the jet and surrounding gas that disturbs the flow and breaks the jet.

The goal of this study is analyzing the processes taking place in the formation of low-viscosity liquid jets in modeling long-term outflow of liquid microjets into the medium with controllable rarefaction similar to that of the open space and rare planet atmospheres, and also development of diagnostics techniques and hardware necessary to study the processes occurring under these conditions. In the experiments, azeotrope mixture of ethanol (95.57 wt.%) and water (4.43 wt.%) was used whose saturated vapor pressure was high at the temperatures under study. The atmosphere composition was not varied in this study.

The study was performed at the gas dynamic vacuum bench LEMPUS-2 of the Novosibirsk State University. The bench has been described in details in [6], the schematic diagram of measurements during the liquid outflow is given in [7]. Observation, photographic work and video (black-and-white) recording of the studied liquid microjet in the mode of continuous outflow from a thin capillary or small-size aperture in a flat wall were performed through optical windows. The detection of the steady liquid flow lasted for several minutes and was limited only by the experiment program. The operating area and liquid jet inside the chamber were illuminated with a uniform light source. The observation area exceeded 0.3 m both in the vertical and horizontal directions.

The initial liquid temperature T_0 was controlled with the accuracy not lower than 0.1 K. The pressure difference ΔP_0 was determined as the difference between pressure P_0 above the liquid measured with a combined pressure-and-vacuum gauge and residual pressure P_b in the vacuum chamber measured with a vacuum gauge. To study the jet outflow into the medium under the atmospheric pressure, the vacuum chamber was filled with gas, while in the vessel with liquid a pressure exceeding the atmospheric pressure was created with a compressor. To implement the modes of liquid outflow into vacuum at pressure differences of < 100 kPa, the vessel with liquid was connected to an independent vacuum pumping system. The continuous steady-state discharge of the liquid was measured at the horizontal outflow from apertures of $d_a = 120, 170, 290\,\mu$m in diameter and vertical (downward) outflow from a thin capillary with inner diameter $d_a = 400\,\mu$m and extension $L/d_a = 63$.

Physical quantities characterizing the modes of vertical ethanol microjets are listed in the Table. The coefficients of surface tension σ and dynamic viscosity μ, as well as ethanol saturated vapor pressure P_s on the phase equilibrium curve were taken from handbooks and GOST [8]. To estimate the ethanol overheating (the depth of entry into the metastable area), both absolute and relative parameters were used: $N_s = P_s/P_b$ [9] for pressure and $\Delta T_s = T_0 - T_s$ [10] for temperature.

Photos of the ethanol jets for some of the modes presented in the Table are shown in Fig. 1. In the center parts of photo tops, light-color images of the capillary ends are shown. For better clarity, the photos are given in different scales. In the left corner of the photo top, a scaled section of the fixed length (20 mm) is placed, which allows estimating the sizes of different jet sections. The microjet shown in the photos is observed from the nozzle outlet as a dark (almost black) narrow long cylinder that becomes

Modes of vertical ethanol jet outflow from the capillary

Mode No.	T_0, K	σ, mPa $\cdot$ m	μ, mPa $\cdot$ s	P_s, kPa	P_b, Pa	N_s	T_s, K	ΔT_s, K	ΔP_0, kPa
1	295	22	1.16	5.81	10^5	0.06	295	0	100
2	295	22	1.16	5.81	10^5	0.06	295	0	20
3	295	22	1.16	5.81	600	9.68	262	33	100
4	295	22	1.16	5.81	600	9.68	262	33	20
5	295	22	1.16	5.81	2	2905	201	94	100
6	295	22	1.16	5.81	1	5810	196	99	20

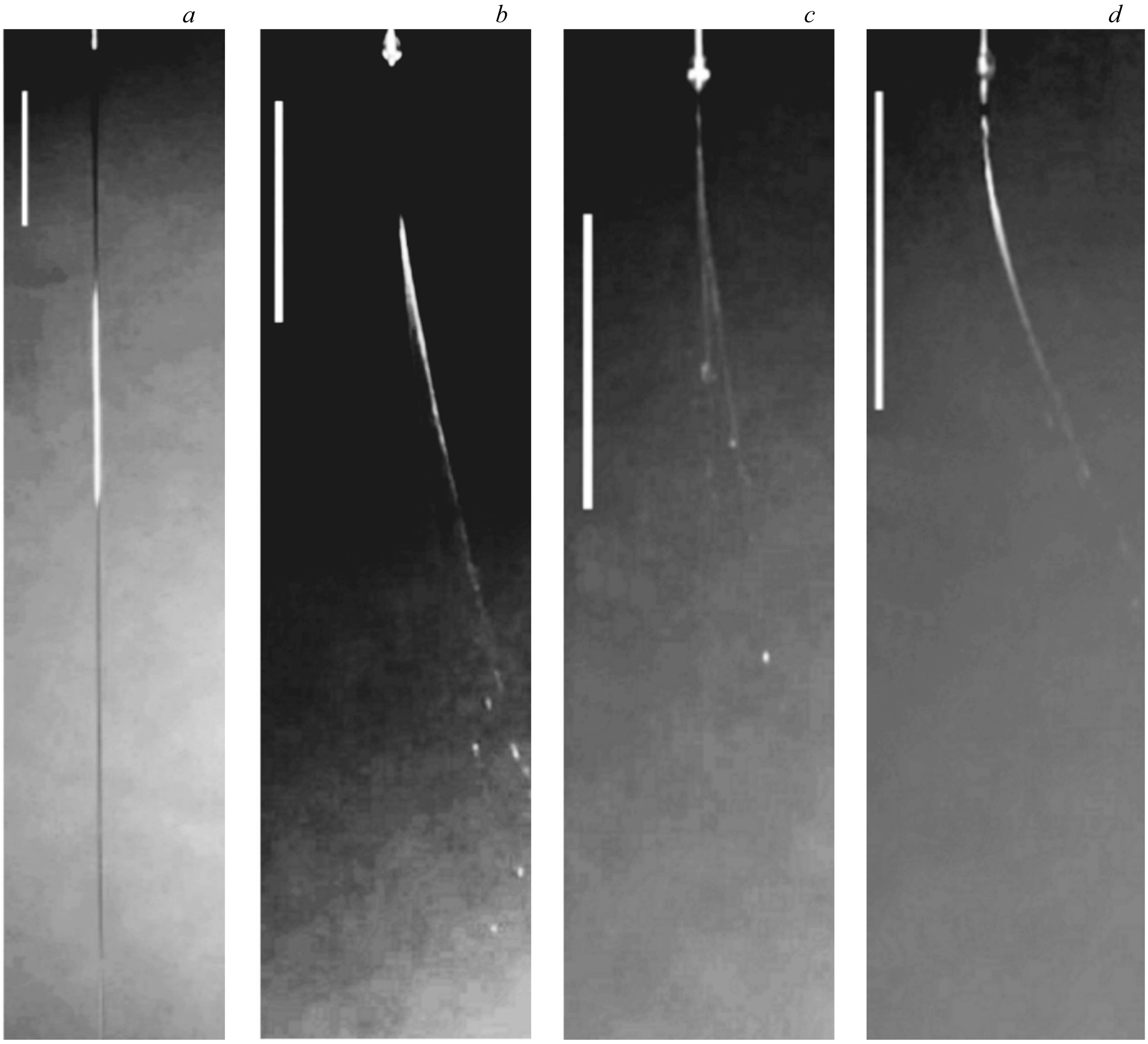

Figure 1. Ethanol microjets, outflow from the capillary: a — into the atmosphere, mode 1; b — into vacuum at the pressure difference $\Delta P_0 = 100$ kPa, mode 3; c, d — into vacuum at the pressure difference $\Delta P_0 = 20$ kPa, modes 4 and 6, respectively.

light quite sharply. The photos were selected from a series of video records made at the shooting speed of 30 fps. The recording time allowed registering the flow stationary periods and their sudden changes at constant pressure and temperature. Since the number of pictures and fragments was limited, we could not represent a fairly large number of various shapes of nonstationary flows. Fig. 1,a) presents the microjet photos made in modes 1, 3, 4 and 6, respectively (see the Table). Contrary to the outflow into the atmosphere (Fig. 1,a), the microjet outflow into vacuum (Fig. 1,b–d) is characterized by spontaneous changes in the jet shape and character. Analysis of the results obtained show that

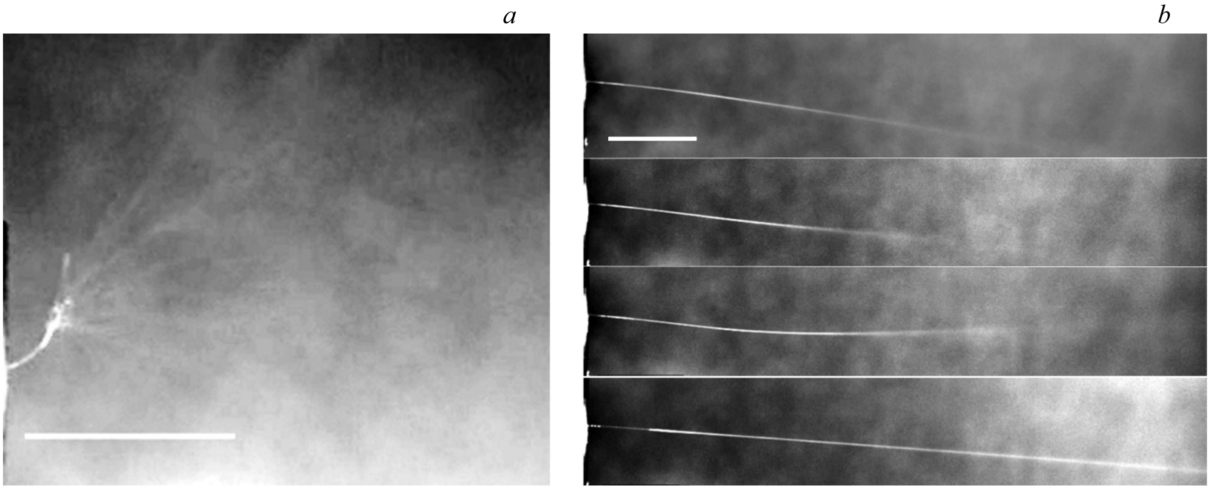

Figure 2. Ethanol horizontal outflow from the aperture $d_a = 120\,\text{mm}$ in diameter at $T = 295\,\text{K}$. a — $\Delta P_0 = 16\,\text{kPa}$, $P_b = 0.4\,\text{Pa}$; b — $\Delta P_0 = 100\,\text{kPa}$, $P_b = 1\,\text{Pa}$ (the microjet at the moments selected subsequently)

the microjet instability increases with decreasing pressure difference between that above the liquid and that in the outflow chamber. Formation of curvilinear jets is a general tendency. The existence of heterogeneous nucleation centers promotes the downstream „explosive“ boiling-off of the jet with formation of a cone-like vapor-liquid jet with cone angles of up to 60° depending on the pressure difference at the nozzle.

Horizontal microjets studied in this work simulated the liquid discharge into vacuum through a small-size aperture (Fig. 2). The experiments showed that horizontal microjets are characterized by a stronger instability and diversity of curvilinear shapes. Boiling-off or spraying, as well as sudden changes in the flow direction, occurs as a rule after emergence of peculiarities characterized by brighter reflected light and changes in the jet local geometry at the bifurcation point. Vaporization, as well as the vapor-gas phase expansion, are of the spontaneous character. When the pressure difference is low (Fig. 2, *a*), the outflowing horizontal microjet can suddenly and sharply bend up. In this case, a „club-like“ crown arises at the end section, after which the jet passes to the state of „explosive“ spraying. The projection cone angle of particles moving almost straight (that evidences a high initial speed of the particles) exceeds 90°.

Fig. 2, *b* demonstrates spontaneous changes in the direction and shape of the microjet outflowing from the aperture $120\,\mu\text{m}$ in diameter at the aperture pressure difference of 100 kP during subsequent (downward) time intervals. Molecular forces acting in the jet are so high that their result exceeds that of the gravity force and causes such changes in the microjet flow direction that are not consistent with the flow shape in the gravity field. The flow direction change cannot be explained by specific features of the video recording. The flow shape shown in each photo remains stable for certain (not equal) time intervals, and changes occur almost instantly. Notice that sharp changes in the jet direction and shape took place typically after a sudden formation of a short section with brighter glowing observed in analyzing the video record.

The observed changes in the microjet shapes may be assumed to be caused by intense evaporation from the surface of the overheated ethanol jet and reaction effect of the emerging vapor. The observed shapes may be explained under the model of the flow barocapillary instability described in [11,12]. According to this model, the flow destruction is caused by the overheated liquid evaporation mainly from the surface cavities formed due to the capillary instability. The surface cavities enhance the heat flow towards the cavity and evaporation from its surface, and also increase the vapor reaction effect on the surface thus accelerating the cavity extension. The reaction effect of the vapor jet from the formed cavity or a chain of cavities changes the jet direction. The surface cavities of the overheated flow may collapse under the evaporated liquid reaction effect on their surface. When the pressure difference decreases, the jet becomes shorter and less stable, and the microjet sprays at a less distance from the nozzle.

Thus, in analyzing long-term discharge of liquid microjets into vacuum (a strongly rarefied medium), certain differences were revealed in the processes of discharging both from an aperture and long capillary from those described in literature [9,13–15]. First of all, this is an extreme instability of the flow shape that remains relatively stable in measuring for very short time intervals. In addition, it was shown that it is possible to model complex processes of microliquid outflow into a medium with preset rarefication using a compact vacuum gas-dynamic bench.

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Conflict of interests

The authors declare that they have no conflict of interests.

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