Influence of individual roughnesses nozzle edge on the length of the supersonic section of an underexpanded microjet

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Abstract. The paper presents the results of the experimental investigation of the influence of a small group of roughnesses uniformly located on the edge of the convergent nozzle on the length of the supersonic core of an underexpanded air microjet. The tests are carried out on the low-pressure test bench with the aid of the Pitot tube. The set of nozzles with the diameter of 2 mm, with the smooth output edge and the edge of the similar shape roughnesses (from 2 to 4) is used. The underexpanded microjets flowing out from the nozzles of the diameter 10.6; 16.1; 21.4, and 34.8 μm are simulated by the outflow Reynolds number. It is shown that the presence of roughnesses can reduce essentially the supersonic section length and eliminate the previously found effect of microjet “relaminarization”, however the reduction value dubiously depends on the amount of the roughnesses on the nozzle edge.

1. Introduction
The influence of nozzle edge roughness on the measurement results is a serious challenge in the research of gas dynamics and stability of gas microjets. In particular, analysis of the roughness effect on the length of the supersonic core of axisymmetric underexpanded microjets is of interest. Since the length of the supersonic section depends on the intensity of the jet flow and ambient gas mixing, the supersonic section length should be influenced by the disturbances created by the roughness elements on the nozzle edge. Among them, the lengthwise stationary vortex structures are the best studied; they can gain in the underexpanded jets because of the positive curvature of the jet flow boundary [1, 2]. The vortex structures generated by the roughness can form initial running disturbances amplifying in the jet flow shear layer and resulting in the flow tubulisation and reduction of the length of the jet supersonic section. Note that most investigations in this field are made for completely turbulent macrojets.

The important peculiarity of the microjets is the moderate outflow Reynolds numbers which rarely exceed 5,000. Only the laminar and transition modes of the jet flow lie in this range. Moreover, we fail to produce the perfectly smooth surface of the output edge during the manufacture of the real convergent micronozzle. There are always relatively large humps and cavities of uncontrolled size and amount (see, for instance, [3, 4]). Because of small sizes of the micronozzles, it is difficult to connect the measured disturbances of the jet flow field with specific roughnesses on the micronozzle edge.

This paper presents the measurements of the length of the supersonic core of the axisymmetric underexpanded air jets flowing put from the smooth convergent nozzle with the roughnesses of the same size and shape uniformly imposed on the output edge – but the quantity of the roughnesses varies from two to four. Such an approach permits understanding the influence of a single roughness on the jet
stability and mixing process intensity, plus finding the possible mutual influence of the disturbances in the jet flow from each individual roughness.

2. Experimental equipment and measurement technique
The experiments are carried out on the jet low-pressure test bench described in [5]. The test bench permits independently maintaining the jet outflow Reynolds number $Re_d$ and jet underexpansion degree $n$. The experiments involve the convergent axisymmetric nozzle with the diameter 2 mm. [5] previously showed the possibility to simulate the micronozzles by the millimeter-diameter nozzles by $Re_d$. In particular it was demonstrated that the dependencies of the supersonic core length on the underexpansion degree value $n$, obtained for the jets flowing out from the micron and millimeter nozzles, coincide in quantity as the outflow Reynolds numbers $Re_d$ are equal. The framework of this approach, in the experiments the outflow of the underexpanded air jets from the nozzles diameter 10.6; 16.1; 21.4 and 34.8 $\mu$m was simulated in the underexpansion degree range from 1.1 to 6 and outflow Reynolds numbers from 800 to 5000.

Figure 1 presents the scheme of the nozzle itself and nozzle plenum chamber. There was a possibility to rotate the nozzle about the lengthwise axis. The nozzle conicity of $60^\circ$ provides the minimal effect of acoustic wave reflection from the nozzle end face and discrete tone appearance. The output edge of one nozzles was absolutely smooth (nozzle No.1), whereas the output edge of the other nozzles were covered with lengthwise N-shaped scratch marks with the height and deepening $h = 170 \mu$m, width 300 $\mu$m and length 1 mm. There were two scratch marks on the edge (nozzle No. 2), three (nozzle No. 3), four (nozzle No. 4), and they were located uniformly over the nozzle output cross-section circle.

![Figure 1. The scheme of nozzle and nozzle plenum chamber. There are characteristic sizes of the nozzle and chamber, air supply tubes and tubes for the manometer connection.](image)

The measurements in the jet flow were carried out with the Pitot tube, its inner diameter 0.17 mm and outer diameter 0.4 mm. During the experiments, the Pitot pressure $P_0$’ was measured. The tube was connected with a miniature differential pressure gage TDM4-IV1, which forms the Pitot probe. Characteristic pressure relaxation time in the probe was 0.3 s. The probe was installed on the 3-component pointing device, its position alignment accuracy was $\pm 0.1$ mm. The main measurements were performed as the probe moved along the jet axis. Additive measurements were carried out for the Pitot pressure distributions in a number of cross sections of the jet flowing from the nozzle No. 2. The length of the supersonic section of model microjets was found as the distance from the nozzle cut to the point in the axis where the pressure $P_0$’ corresponds to the value of this the pressure for the Mach number 1. The technique of determination of the supersonic section length with the Pitot tube is described in detail in [6].
3. Results and discussion
Figure 2 shows the results of measurement of the length of the supersonic section of $L_c$ air jets rated for the nozzle diameter $d$. The graph (a) corresponds to the model jet flowing out from the nozzle with the diameter (a) — $d = 10.6 \mu m$; (b) — $16.1 \mu m$; (c) — $21.4 \mu m$; (d) — $34.8 \mu m$. The solid, dashed and dash-dot curves on the graphs show the supersonic core length $L_c/d$ versus the jet underexpansion degree $n$, obtained for turbulent macrojets, respectively in [7], [8] and [9].

The graphs show that, as a certain underexpansion degree is reached, the length of the supersonic core of the model jets falls fast to the level typical for the turbulent macrojets. The short-time jump of the supersonic core length after the fall (see figure 2b) results from the jet “relaminarization” effect [4, 10]. The presence of the roughness on the output nozzle edge reduces the value $L_c/d$ and eliminates the “relaminarization” effect. The effect of the supersonic core length reduction appears better for the model nozzles of a bigger diameter. The degree of $L_c/d$ reduction dubiously depends on the roughness amount. The strongest reduction effect is observed for the nozzle No. 2 with two roughnesses. For the nozzle No. 4 with four roughnesses this effect is weak or absent.

Evident that the roughness influence on the jet flow should depend on the relation of the roughness
Figure 3. The roughness height/depth value $h$ to the boundary layer thickness $\delta$ on the output nozzle edge versus the underexpansion degree value $n$ for four diameters of the model micronozzles. 1 – $d = 10.6 \text{ } \mu\text{m}$; 2 – $16.1 \text{ } \mu\text{m}$; 3 – $21.4 \text{ } \mu\text{m}$; 4 – $34.8 \text{ } \mu\text{m}$.

Figure 4. The pressure transversal distributions $P'_0$ in several cross sections of the underexpanded microjet ($n = 2$, the model nozzle diameter $d = 34.8 \text{ } \mu\text{m}$) flowing out from the nozzle No. 2. (a) – dimensionless distance from the nozzle $x/d = 0.3$; (b) – 0.8; (c) – 1.75; (d) – 3.2. The curve 1 is the measurement along the center line passing through the roughness; 2 – along the center line perpendicular to the line 1. The curve 3 is obtained for the smooth nozzle No. 1.
height and depth to the boundary layer thickness on the nozzle edge. To gather the data about
the boundary layer thickness on the nozzle edge, the numerical simulation of the flow in the nozzle settling
camera and in the nozzle conic contraction was made with the ANSYS Fluent package (see the scheme
in figure 1). Figure 3 presents the calculated dependencies of the ratio of the roughness hump/cavity
characteristic size $h$ to the mixing layer thickness $\delta$ on the nozzle edge versus the underexpansion degree
value $n$ for four diameters of the model micronozzles. It is seen that the roughness size is comparable or
exceeds the boundary layer thickness on the nozzle edge within the whole measurement area $n$, and the
roughnesses should influence more intensively on the mean flow in the jet for the model nozzles of the
bigger diameter.

To determine the roughness influence on the mean flow in the jet, we tried to measure the value of
the pressure transversal distribution deformation $P_0'$, created by two roughnesses in the nozzle No. 2
during the simulation of the microjet flowing out from the nozzle with the diameter 34.8 $\mu$m. The Pitot
tube was used to perform the measurements across the jet axis along the center line passing through the
nozzle roughness, as well as along the center line in the perpendicular direction where there were no
roughnesses. Additive measurements were carried out across the axis of the jet flowing out from the
nozzle without roughness (nozzle No. 1). The measurements were performed in the same jet cross
section by the lengthwise axis $x/d$. Figure 4 shows the examples of these measurements. It is evident
that on the graphs there are no significant distortions of the mean flow field, except for the visible jet
expansion along the direction binding two roughnesses on the nozzle No. 2 edge.

One reason of the non-monotony behavior of the supersonic core length vs the roughnesses amount
on the output nozzle edge may be the interaction between the flow disturbances created by the
neighboring roughnesses. The N-shaped roughness along with the flow can create one lengthwise vortex
instead of two counter-rotating vortices. Then the closely located vortices can inhibit each other as the
amount of the roughnesses rises on the nozzle edge. This is probably the explanation of the essential
difference between the supersonic core lengths outflowing from the nozzles No. 1 and No. 4.

The other possible reason of the non-monotony influence of the roughness amount on the supersonic
section length can be the inhibition of the convective instability of the shear layer of the jet lengthwise
vortices created by the bigger amount of roughnesses. Inhibition of the convective instability prevents
the appearance of the global jet flow instability, generation of the jet discrete tone, jet transition in the
turbulent flow mode and reduction of the supersonic core length. The definite answer to the question
about the possible reasons of the non-monotony influence of the roughness amount on the supersonic
core length can be found from the numerical simulation results.

4. Conclusion

The paper presents the results of the experimental investigation of the effect of a small group of the
roughnesses uniformly located on the convergent nozzle edge, on the length of the supersonic core of
the model underexpanded air microjets.

The non-monotony influence of the amount of roughnesses on the length of the supersonic core of
the model microjets. As the roughness amount rises from two to four, the supersonic core length rises
and reaches the values obtained for the smooth nozzle. Moreover, the “relaminarization” effect recovers
in the model microjet. Suggestions about two possible reasons of such an effect of the roughness amount
are proposed:

- mutual inhibition of the closely located lengthwise vortices created by the neighboring
  roughnesses;
- inhibition of the convective instability of the mixing layer of the jet lengthwise vortices.

Acknowledgment

This study was funded by the Russian Science Foundation (Grant No. 17-19-01157).

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