Investigation of the effect of an acoustic field on the flow regime of a microjet

B V Perepelitsa
Kutateladze Institute of Thermophysics SB RAS, 1 Ac. Lavrentiev Ave., Novosibirsk, Russia
E-mail: perep@itp.nsc.ru

Abstract. A detailed visual study of the structure of a circular laminar micro-jet flowing into the atmosphere under the influence of an acoustic field was carried out. A jet of air flowed out of the profiled glass nozzle with a diameter of 500 microns. Characteristic vortex and coherent structures and zones with intense turbulent mixing were found in the flow. The features of the formation of vortex structures in a laminar jet under the influence of the acoustic field and the vibrational-rotational flow regime in the jet at the outlet of the nozzle were identified.

1. Introduction
Interest in the study of micro hydrodynamics in jets, mini-and micro channels against the background of general miniaturization of technological devices plays an important role in the creation of new different technologies. It became possible to use mini-and micro-jets in such processes as mixing of various chemical and biological reagents, micro cooling of electronic devices, microprocessor processing, production of nanopowders, etc. However, one of the reasons for the relatively small number of studies in this area is due to the complexity of high-precision experimental measurements in small volumes. The main experimental methods used in the studies of mini-and micro-flows are visual methods, thermal anemometry, optical methods PIV (Particle image velocimetry) and other. Visual methods of studying the flow are used to obtain a clear picture of the flow for the possibility of building the adequate theories and performing calculations [1].

One of the first works devoted to the experimental study of the flow pattern and stability of macro- and micro-jets at different Re numbers and influence of acoustics on them is the research [2-14]. The authors of [3-9] indicate the presence of a long laminar part of the jet reaching hundreds of diameters. The authors of [5, 6] suggest that the presence of an extended laminar region in micro-jets is due to the presence of a parabolic velocity profile at the nozzle exit, where Kelvin–Helmholtz instability in the jet mixing layer does not develop. In [2-14] the results of a large series of experimental studies of the structure and features of evolution in subsonic round and flat macro-and micro-jets and the influence on their acoustic effects are presented. New effects have been found under the influence of a transverse acoustic field on micro-jets, such as the transformation of a circular micro-jet into a flat one, the oscillation of the jet as a whole, and the effect of splitting the micro-jet into two jets [5, 6], which develop independently (bifurcation) at different flow parameters. The purpose of the acoustic influence on the jet is to provide solutions to various problems, including the formation and interaction of various vortex structures, in order to study in detail the specific mechanisms of such interaction. The flow of micro-jets in narrow channels with a wide variety of flow regimes is of particular interest [15,16].
2. Experimental setup and measurement methods

The focus of this paper is to examine the effects of a transverse acoustic field on a laminar microjet and to study the thus-formed characteristic vortex structures and their instability. Evolution of the microjet structure visualized by light scattering particles (fume) was recorded by a photo-video camera. We studied the process of vortex structures evolution in a laminar round microjet and the mechanism of its turbulization under the influence of transverse acoustic field. The experimental bench was an air circuit consisting of a nozzle, a fume generator, and a piston pump or high pressure cylinder. A detailed description of the experimental setup is given in [12]. The flow rate was determined from the air volume displaced by the piston per unit time or using a float flow meter.

In the experiments, axisymmetric microstrain flowing from a glass micro nozzle with an inner diameter of 500 µm was used. Air was used as the working gas. The average jet flow rate at the nozzle outlet was varied from 0.4 to 50 m/s. The studies were conducted in the range of Reynolds number from 38 to 2500 (Re = \( \frac{W \cdot D}{\nu} \)), where \( W \) is average flow rate, \( D \) is inner diameter of the nozzle, and \( \nu \) is kinematic viscosity of air). The source of acoustic disturbances was a Hertz HS-165 dynamic head installed at a distance of 20 cm from the nozzle so that the acoustic generator plane was parallel to the pipe axis. The intensity of the acoustic waves was controlled to 110 dB. The frequency of acoustic oscillations was varied from 30 to 2000 Hz. Visualization of the flow pattern was carried out by photo and video recording. The light-emitting and halogen incandescent lamps illuminated the observation zone uniformly. The lighting was chosen so as to obtain sufficiently clear pictures of the flow structure. The field of view was also chosen so that to identify clearly the characteristic structures formed in the flow. To visualize the flow, fume with a particle size of about 1 ÷ 2 microns was added into the air. Shutter speed when shooting was 1/16000 second. A rather short shutter speed of recording allowed us to get clear photos and reveal specific features in the stream structure. Analysis of some photos of the flow picture has revealed the existence of characteristic large and small-scale structures in the jet under the action of acoustic field. Visualization made it possible to determine the spatial pattern of the flow: at first, there is the laminar jet, then the jet oscillates and transforms into the turbulent flow.

Flow visualization of the subsonic microjet with the diameter of 500 µm is shown in Fig. 1. In our experiments for a circular microjet at low Re numbers, we mainly observed a spiral instability regime (Fig. 1 b). As it can be seen from the figure, at Re = 41 and more, in the flow there is a sector of laminar flow at Re = 2650, the transition to turbulence is observed immediately at the outlet of the nozzle. It follows from experiments that jet length to the transition point \( L \) (jet range) can be \( (200 \div 2)D \), i.e., the lengths of the laminar and transitional regions of the microjet are sufficiently larger. The obtained data on the length of the laminar partition of the micro-jet agree satisfactorily with the data given in [8].

![Figure 1](image-url)

**Figure 1.** Visualization of the flow of a air microjet without acoustic action (nozzle \( D = 500 \mu m \), Re from 40 to 2650).
The acoustic effect on the jet at different Reynolds numbers results in different kinds of flow and a wide variety of jet shapes and vortex structures. The question about the influence of initial conditions on development of the jet flows is sufficiently studied for the turbulent regime and it is studied insufficiently for the laminar-turbulent transition. The theory confirms that the jets with parabolic initial velocity profile have the higher Reynolds numbers than those with the impact (“top-hat”) velocity distribution, but the Re number of transition does not exceed 10 ÷ 30 [6].

![Figure 2](image1.jpg)

**Figure 2.** Vortex structure formation in a laminar jet under transverse acoustic field (Re = 245, f = 100 ÷ 700 Hz).

Figure 2 shows pictures of the jet structure at constant Reynolds numbers with acoustic effects of 100 ÷ 700 Hz. At the initial stage, a turbulent flow zone forms at a certain distance from the nozzle. Then, with increasing frequency, the amplitude of perturbation oscillations in the jet increases and can reach significant values. The angle of disintegration of the jet reaches 30 degrees. At the same time, the modes can be identified when fairly simple vortex structures and sinusoidal oscillations are formed in the jet stream, depending on the frequency of the sound distance. At the initial stage, at a certain distance from the nozzle, characteristic structures are formed, then with increasing frequency, amplitude of disturbance oscillations in the jet increases and can reach significant values. The wavelength of sinusoidal oscillations is of an order of magnitude greater than the diameter of the nozzle. With increasing frequency of acoustic influence in this range the area of laminar flow decreases.

![Figure 3](image2.jpg)

**Figure 3.** Visualization of the flow of an air microjet (nozzle D = 500 μm, Re = 430, a – f = 100 Hz and b – f = 300 Hz).
Another version of the formation of vortex structures can be seen in Fig. 3 (Re = 430, \( a \) - \( f = 100 \) Hz and \( b \) - \( f = 300 \) Hz). It should be noted that the shape of the jet is non-stationary and changes from frame to frame in constant flow conditions. In this case (except in [6]) at the nozzle outlet the flow is transient, i.e. the jet oscillates, rotates and deforms locally, acquiring a complex shape. Formation of short-wave vortex structures is possible (marked with arrows). In some cases, it is possible to observe the bending of the laminar part of the jet. Downstream, the vortices disintegrate and the jet becomes turbulent. At the same time, emissions from the jet can be observed in the initial turbulence section at almost a right angle.

![Figure 3. Vortex structure formation in a laminar jet under transverse acoustic field (Re = 60 ÷ 245, f = 350 Hz).](image)

![Figure 4. Vortex structure formation in a laminar jet under transverse acoustic field (Re = 60 ÷ 245, f = 350 Hz).](image)

Other variants of the jet flow are also possible, they are shown in Fig. 4 (Re = 60 ÷ 245, \( f = 350 \) Hz). At the nozzle outlet, sinusoidal instability occurs. In this case as in Fig. 3 at the nozzle outlet the flow is transient, that is, the jet oscillates, rotates and becomes locally flattened. The length of this zone is about 20 calibers where you can see the bending and flattening of the jet. Further evolution and decay of the jet lead to rapid turbulization of the flow. The turbulization of the jet occurs very vigorously, and further formation of the conical shape of the flow is observed on average.

Deeper understanding of the observed effects requires a detailed 3D qualitative and quantitative research.

**Conclusions**

From the results of the visual study of microjet structure evolution under transverse acoustic field we can draw the following conclusions:

1. It is shown that the range of free jets could reach 2 ÷ 200 nozzle calibers. The Reynolds number of transition to turbulence in the mini- and microjets takes large values (2600), and it is three orders of magnitude higher than the Reynolds number of stability loss (10 ÷ 30) in the macrojet.

2. It has been determined that at the nozzle outlet the flow is transient: the jet oscillates, rotates, and deforms locally acquiring a flattened shape. Further evolution and disintegration of the jet lead to rapid turbulization of the flow.

3. It is shown that twisting of the micro-jet in the direction of the velocity vector is observed both with and without acoustic influence.

4. It is found that under the action of the acoustic field in the jet the short wave vortex structures can be formed.
Acknowledgement
This work was carried out under the state contract with IT SB RAS.

References
[1] Van Dyke, Milton *An album of fluid motion* 1982 (Stanford, CA: Parabolic Press) p 176
[2] Reynolds A J 1962 *J. Fluid Mech.* **14** 552
[3] Becker H and Massaro T A 1968 *J. Fluid Mech.* **31** 435
[4] Chie Gau, Shen C. H., Wang Z. B. 2009 *Physics of Fluids.* **21** 701
[5] Fomin V M, Aniskin V M, Maslov A A et al. 2010 *Dokl. Phys.* **55** 419
[6] Kozlov V V, Grek G R, Litvinenko Yu A, Kozlov G V, Litvinenko M V 2011 *J. Eng. Therm.* **20** (3) 1
[7] Litvinenko Y A, Grek G R, Kozlov V V, Kozlov G V 2011 *Dokl. Phys.* **56** 26
[8] Lemanov V V, Terekhov V I, Sharov K A et al. 2013 *Technical Physics Letters* **39** (5) 421
[9] Aniskin V M, Buntin D A, Maslov A A 2012 *Tech. Phys.* **57** 174
[10] Krivokorytov M S, Golub V V, Volodin V V 2012 *Tech. Phys. Lett.* **38** 478
[11] Aniskin V M, Lemanov V V, Maslov N A, Mukhin K A, Terekhov V I and Sharov K A 2015 *Techn. Phys. Letters* **41** (1) 46
[12] Perepelitsa B V 2017 *J. Eng. Therm.* **26** (1) 91
[13] Perepelitsa B V 2018 *J. Eng. Therm.* **27** (2) 1
[14] Perepelitsa B V 2018 *J. Phys.: Conf. Ser.* **1105** 012003
[15] Perepelitsa B V 2013 *Modern Sien.* **1** (12) 134–40
[16] Perepelitsa B V, Shestakov M V 2009 *Tepl. Aeromekh.* **16** (1) 226