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

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Abstract. The paper presents the results of visual study of the structure of a round minijet flowing into the atmosphere exposed to an acoustic field. The studies were performed with the laminar jet flow. According to the photo and video recording of the flow pattern we revealed characteristic features of the jet structure in the acoustic field. Characteristic vortex structures and zones with intense turbulent mixing were detected in the flow. We revealed the process of vortex structures formation in a laminar jet under the effect of the acoustic field, vibrational and rotational regimes of jet flows at the outlet of the pipe 1.35 mm in diameter. The present study is the continuation of the research on a minijet structure in an acoustic field [10].

1. Introduction
In recent years, interest in the study of mini- and microflows has increased significantly, which is associated with the development of fundamentally new technological microdevices. Investigation of microhydrodynamics in the mini- and microchannels on the background of the overall miniaturization of technological devices plays a decisive role in the creation of various new technologies. It has become possible to use mini- and microjets in such processes as microcooling of electronic devices, microprocessing, the nanopowder production, mixing of microvolumes of solutions in the chemical and biological industries, etc. One reason for the relatively small number of studies in this field is caused by the complexity of the high-precision experimental measurements in small volumes. The basic experimental methods used in studies of mini- and microflows were visualization and thermal anemometry. Flow visualization is the art and science of obtaining a clear image of a physical flow field and the ability to capture it on sketch, photograph or other video storage device. Flow visualization plays an important role in fluid mechanics, as a search tool for general information about the flow [1]. In recent years, studies carried out by means of the PIV (particle image velocimetry) method are widely used. A pioneer studies devoted to the experimental investigation of the stability of the macro- and microjets at various Re numbers under effects of acoustics are presented in [2–9]. The authors of [3–9] indicate the presence of a substantially long laminar jet portion reaching hundreds of diameters. The authors of [5, 6] have suggested that the presence of a stretched laminar area in the microjet is caused by the presence of a parabolic velocity profile at the nozzle outlet, whereby the Kelvin–Helmholtz instability does not develop. It is known that in macrojets the transition from a laminar to turbulent flow is caused by the development of Kelvin–Helmholtz instability in the jet mixing layer. In [1–10], the authors presented results of a large series of experimental studies of the structure and the characteristics of evolution of subsonic round and plane macro- and microjets. They showed the features of evolution of these flows in relation to changes in
the initial conditions at the nozzle outlet and acoustic action. New effects have been found under the impact of the transverse acoustic field on microjets, such as transformation of a round microjet into a plane one and effect of microjet splitting into two jets [5, 6], which evolve independently (bifurcation) at various flow parameters. The purpose of the acoustic impact on the jet is to provide a basis for solving various problems, including the interaction between different vortex structures in order to explore in detail the specific mechanisms of such interaction. The flow of microjets in narrow channels, where there is also a wide variety of flow modes, is of particular interest [11, 12].

2. Experimental parameters and discussion
The focus of this paper is to examine the effect of a transverse acoustic field on a laminar minijet and to study the thus-formed characteristic vortex structures. Evolution of the jet structure visualized by light scattering particles (fume) was recorded by a photo-video camera. We conducted research of the vortex structures evolution process in a laminar round jet and the mechanism of its turbulization under the action of transverse acoustic field. The test bench was an air circuit consisting of a nozzle, a fume generator, and a piston pump. The test bench is shown in figure 1. A detailed description of the experimental setup is given in [10]. The flow rate was determined based on the air volume displaced by the piston per unit time. The jet flowed out from a metal pipe with an inner diameter of 1.35 mm and a length of 20 mm. The average jet flow rate at the nozzle outlet was varied from 0.4 to 3 m/s. The studies were conducted within the range of Reynolds number from 38 to 250 (Re = WD/ν, where W is average flow rate, D is inner diameter of the pipe, and ν 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 sound intensity reached 120 dB. The frequency of acoustic oscillations was varied from 30 to 1000 Hz. Visualization of the flow pattern was carried out by photo and video recording. The light-emitting and halogen incandescent lamps uniformly illuminated the observation zone. 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 clearly identify 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. A digital photo-video camera, 50 frames/s, 1/4000 s and exposure performed video recording. In the course of the visual investigation we obtained series of images of fume distribution in the jet after 20 ms. A sufficiently short recording exposure allowed for sharp photos and identifying characteristic features in the flow structure. Analysis of some photos of the flow picture has revealed the presence of characteristic large and small-scale structures in the jet under the action of acoustic field.

Figure 1. Vortex structure formation in a laminar jet under transverse acoustic field (Re = 44, f= 78 Hz). (pictures obtained after 20 ms).
The acoustic effect on the jet at different Reynolds numbers results in different kinds of flow and a wide variety of vortex structures. At the same time, one can identify regimes when quite simple vortex structures are formed in the jet flow. Figure 1 shows a picture of formation of a single vortex (pictures obtained after 20 ms). The sound source is to the left of the jet. At the initial stage at a certain distance from the nozzle a characteristic structure is formed, then the structure is deformed to a thin bent leaf and begins to fold into a vortex increasing in diameter with time. The vortex acquires a conical shape. We can note that the formed vortex moves downward the flow practically at a constant velocity.

Another version of vortex structures formation can be seen in figure 2 (Re = 175, f = 200 Hz). In this case (other than in [6]) at the nozzle outlet the flow is transient, that is, the jet oscillates, rotates and deforms locally acquiring a flattened shape. The length of this zone is about 12 calibers. Before the turbulence of the jet starts developing, one can observe the formation of a vortex structure. Further evolution of the jet and its disintegration have a certain regularity. Before the disintegration of the jet and its turbulization, jet oscillations occur with formation of a characteristic vortex structure. A row of vortex structures is formed at the flow edges; the rows are linked in a complicated manner both in one row and between the rows. Down the flow the vortices disintegrate and the jet becomes turbulent.

Other options of the jet flow are also possible, they are shown in figure 3 (Re = 245, f = 350 Hz). At the nozzle outlet, sinusoidal instability occurs. In this case (other than in [6]) as in figure 3 at the nozzle outlet the flow is transient, that is, the jet oscillates, rotates and becomes locally flattened shaped. The length of this zone is about 7 calibers. Further evolution of the jet and its disintegration become regular to some extent. Before the disintegration of the jet and its turbulization, there occur oscillations and interlacing of the jet followed by formation of vortex structures. We can also observe jet bifurcation, and its separation into three flows. On the sides of the bifurcated jet we see regular complex vortex structures that are interlaced. Other options of the jet flow are also possible, they are shown in figure 4 (Re = 177, f = 200 Hz). At the nozzle outlet, sinusoidal instability occurs. In this case as in figure 3 at the nozzle outlet the flow is transient, that is, the jet oscillates, rotates and becomes locally flattened shaped. The length of this zone is about 14 calibers. Further evolution of the jet and its decay leads to rapid turbulence of the flow. Deeper understanding of the observed effects requires a detailed 3D qualitative and quantitative research.

Figure 2. Vortex structure formation in a laminar jet under transverse acoustic field (Re = 175, f = 200 Hz) (pictures obtained after 20 ms).
3. Conclusions
Visual study of jet structure evolution under transverse acoustic field allows drawing the following conclusions:
1. We have discovered the process of onset and evolution of a single vortex structure in a laminar jet under the action of a transverse acoustic field.
2. It has been determined that at the nozzle outlet the flow is transient, i.e. the jet oscillates, rotates, and deforms locally acquiring a flattened shape. A single vortex may form before jet turbulization.

3. It has been found that bifurcation of the jet may occur, that is, it is separated into three flows.

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