# ESCAPE OF A TURBULENT JET UNDER THE EFFECT OF ACOUSTIC PERTURBATIONS

N. N. Ivanov

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Results are presented of experimental investigations of the local effect of acoustic oscillations of different frequency and constant intensity on the root part of a nonisothermal axisymmetric subsonic turbulent jet escaping from a gas jet atomizer at a different velocity in the $S=0.053$-$3.84$ range of Strouhaille numbers. Data have been obtained indicating the presence of unstable escape modes of a subsonic turbulent jet in an acoustic field; experimental dependences are presented of the relative aperture of the turbulent jet flowing in an acoustic field as a function of various parameters.

It has been disclosed in a number of papers, for instance [1-7], that the effect of sound oscillations on flames and laminar and turbulent jets, in addition to other effects, can result in a loss of stability and the formation of vortices, as well as to some change in the aerodynamic characteristics of the jet flows. It has been established experimentally [4] that a nonlinear dependence defined by the velocity of the gas escape and the ratio between the natural frequencies of vortex formation and the frequency of the acoustic perturbation exists between the change in vortex intensity and the magnitude of the acoustic perturbation.

Experimental Setup and Apparatus. The investigations were conducted on the setup whose diagram and description are given in [8].

The escape of a nonisothermal, axisymmetric, subsonic turbulent jet into an acoustic field was investigated on this setup together with the measurements of the mean velocity and longitudinal intensity of turbulence, and the magnitude of the relative turbulent jet aperture was also determined as a function of different parameters.

Preheated air, taken off from a low-pressure network, was used as the working body supplied to the gas jet atomizer with $d_0=16$ mm output diameter in this paper. The air was heated by an electric heater; the gas jet temperature was raised to approximately $T\approx 373°K$. The temperature was recorded by a chromel–copel thermocouple, whose readings were recorded by an electronic potentiometer of ÉPP-09 type.

Acoustic perturbations of different frequency and constant intensity, delivered to the root part of the turbulent jet, were shaped in the mouthpiece of the acoustic apparatus described in [8].

Investigations conducted by using a measuring probe of an electric thermoanemometer of type ÉTA-5A showed that a plane traveling sine wave is propagated in the output section of the mouthpiece of the acoustic unit. The loud-speakers of the acoustic unit were connected through a matching transformer and low-frequency amplifier of UM-50 A type to a 3G-14 pure tone generator which could be used to vary the frequency and intensity of the acoustic signals smoothly. The characteristics of the input and output signals of the acoustic unit were checked by cathode oscillographs. The visualization of the escape pictures as both an unperturbed turbulent jet and a jet subjected to acoustic perturbations at its root was by an optical method using a serial shadowgraph of type IAB-451, a pulsed light source, and a DRSh-250 mercury lamp.

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The exposure time to obtain the averaged shadow photographs picturing the escape of the turbulent jet was $\tau = 0.0125$ sec.

The pulsed light source permitted obtaining shadow turbulent flow pictures with a $\tau \approx 10^{-6}$ sec exposure. The Reynolds number varied between $3.47 \cdot 10^3$ and $4.17 \cdot 10^4$ according to the atomizer output diameter and the jet escape velocity.

The intensity of the sound oscillations was I = 100 dB = const in all the tests. The dimensionless Strouhal criterion S varied between 0.053 and 3.84, the velocity at the exit from the gas-jet atomizer $u_0$ varied between 5 and 60 m/sec, the frequency of the acoustic signals $f$ fluctuated in a band from 200-1200 $\sec^{-1}$, the wavelength of the acoustic oscillations was correspondingly

$$\lambda = a/f = 1.74 - 0.28 \text{ m}$$

The magnitude of the relative jet aperture angle $\alpha_m/\alpha_0$ determined by processing the negatives on a 5PO-I type microphotometer was used to construct the test dependences. Here $2\alpha_m$ is the aperture angle of the turbulent jet under the effect of acoustic perturbations at its root, and $2\alpha_0$ is the aperture angle of the unperturbed turbulent jet.

Each escape mode of the turbulent jet on whose root acoustic perturbations were applied was recorded twice on photographic film; at $\tau \approx 1 \cdot 10^{-6}$ sec and $\tau = 0.0125$ sec exposures. The length of the transition section to turbulence was determined from the instantaneous Toepler negative projected on the microphotometer screen. Because this transition never occurs at a point, the point corresponding to contraction of the jet after the first large-scale vortex and preceding an essential increase in the jet mixing zone was conditionally taken herein as the "transition point" in conformity with an assumption of A. A. Pavel'ev.

Afterwards, the instantaneous Toepler negative was replaced by an averaged Toepler negative on which the side boundaries of the escaping turbulent jet had been clearly recorded. The length of the transition section to turbulence, which had been determined earlier, was laid off on the screened image of the averaged negative. The initial boundary section of the portion of the jet whose aperture angle must be determined was therefore obtained. The vertex of the potential well, located at a distance $x/d_0 \approx 4.0$ from the atomizer exit, as thermocouple measurements showed, was taken as the final boundary section herein. The aperture angle of the turbulent jet was determined within these boundaries, after which the relative aperture angle $\alpha_m/\alpha_0$ was computed.

Results of the Investigations. Processing of a large number of negatives with recorded escape modes of a turbulent jet in an acoustic field showed that the dependence between the magnitude of the relative jet aperture angle $\alpha_m/\alpha_0$ and the parameters S, $u_0$, and $f$ is complex for the fixed acoustic signal intensity I = 100 dB = const and is nonmonotonic in nature.

It is known [9, 10] that the outer boundaries of a freely expanding turbulent jet have a constant and quite bounded aperture angle $2\alpha_0 = 15\text{-}25°$ in an ordinary initial stream turbulence.

A typical shadow photograph of the escape of an unperturbed turbulent jet from a gas-jet atomizer with $d_0 = 16$ mm exit diameter at $u_0 = 25$ m/sec, while expanding into a medium at rest with a temperature $T_0 = 293°$K, is presented in Fig. 1a. On the basis of experimental results, the initial aperture angle of the unperturbed turbulent jet was selected equal to $2\alpha_0 = 15°$. It was detected that imposition of acoustic perturbations on the root part of the turbulent jet for definite combinations of the parameters $u_0$ and $f$ when I = 100 dB = const results in an increase in the aperture angle $2\alpha_m$ as compared with the value of the initial angle $2\alpha_0$ (the effect of fanlike expansion).

The reaction of a nonisothermal axisymmetric subsonic turbulent jet to acoustic perturbations can probably be explained as follows. It is known [1, 2] that the jet foundation at the nozzle has a great tendency to discontinuous flow and a high degree of instability. If perturbations of appropriate intensity were to operate on this part of the jet in an appropriate time period, then the initial escape is spoiled and is not already restored downstream.

Some characteristic shadow photographs illustrating the escape of a subsonic turbulent jet into an acoustic field at different modes for I = 100 dB = const are presented in Fig. 1b-e.

The experimental results obtained showed that an increase in the ratio between the aperture angle of a turbulent jet and the value of the initial aperture angle in the unperturbed jet in the presence of an

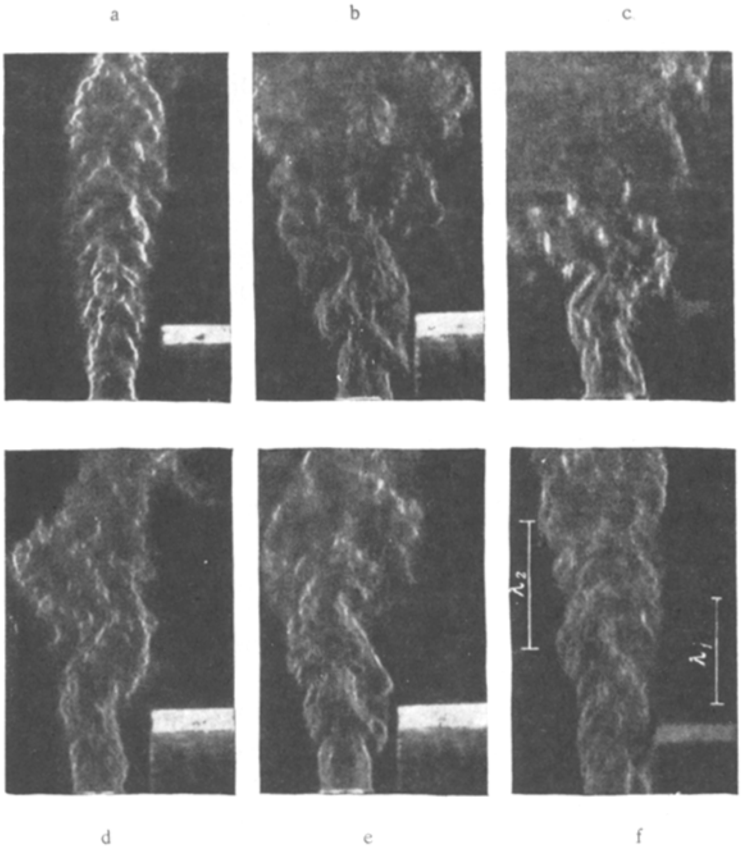

Fig. 1

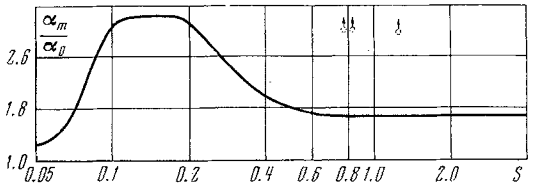

Fig. 2

acoustic signal can fluctuate, for example, between the value $\alpha_m/\alpha_0 = 1.0$ in the $u_0 = 50$ m/sec, $f = 850$ sec$^{-1}$ mode and $\alpha_m/\alpha_0 = 2.75$ in the $u_0 = 40$ m/sec, $f = 500$ sec$^{-1}$ mode (Fig. 1b) and higher.

It can be seen from Fig. 1c how the total collapse of the turbulent jet occurred at a range of approximately three calibers from the exit of the gas-jet atomizer at an escape velocity of $u_0 = 10$ m/sec and an acoustic signal frequency of $f = 258$ sec$^{-1}$.

Modes were successfully exposed in the photographs of the turbulent jet escape process, when the imposition of acoustic perturbations on the root part of the turbulent jet would result in the curving of the jet axis, where this curvature would occur in a plane perpendicular to the optical axis of the IAB-451 shadowgraph. The shadow photograph in Fig. 1d, where the process of turbulent jet escape is shown for $u_0 = 40$ m/sec and $f = 250$ sec$^{-1}$, could be an illustration here. It is seen how the jet axis is twisted at a range on the order of 2.5-3 calibers from the exit of the gas-jet atomizer, then a large-scale perturbation forms in the boundary layer recalling a circular vortex outwardly, after which the jet decomposes.

A shadow photograph on which the initial seed of the large-scale perturbations in the boundary layer is successfully caught is shown in Fig. 1e. The sufficiently clear shadow photographs obtained at $\tau \approx 1 \cdot 10^{-6}$ sec permit us to consider the acoustic frequency of the perturbations being formed in the boundary layer not to exceed $10^6$ sec$^{-1}$.

Cases were observed, for example, at $u_0 = 30$ m/sec, $f = 400$ sec$^{-1}$ (Fig. 1f), when almost periodic perturbations were propagated along the outer contours of the turbulent jet boundary layer, where the troughs of the perturbations being propagated along the right and left contours were approximately cophasal.

Measurements showed that the wavelength $\lambda$ between the almost periodic perturbation troughs is variable in the field of the photographic frame and changes from approximately 1.5 to 2.5 calibers downstream. (The exit diameter of the atomizer $d_0 = 16$ mm is taken as a caliber.)

An investigation of the detailed process of perturbation generation and development in the boundary layer because of the effect of pressure (velocity) antinodes (nodes) of a plane traveling wave at the root part of a turbulent jet is of independent interest but was not carried out herein.

The results of processing the relative aperture angle of a subsonic turbulent jet $\alpha_m/\alpha_0$ as a function of the dimensionless Strouhal criterion $S = f d_0/u_0$ are shown in Fig. 2 for fixed values of the parameter $u_0$. Such combinations of $u_0$, $f$, and I were detected during the course of the experimental investigations, for which partial or total rupture of the turbulent jet would occur. It is impossible to speak about the aperture angle of such jets. Such jet escape modes are provisionally marked by dashed circles with arrows directed upward.

It follows from the results presented that the imposition of acoustic perturbations on the root part of a turbulent jet in the range of Strouhal numbers $S = 0.053$–$3.84$ results, in the majority of cases, in an increase in the aperture angle of the turbulent jet, where the dependence $\alpha_m/\alpha_0 = \varphi_1(S)$ is complex and nonlinear for $u_0 = \text{const}$ and $I = 100 = \text{const}$.

It can be seen from Fig. 2, where the solid line shows the upper boundary of the experimental results, that the greatest values of the parameter $\alpha_m/\alpha_0$ are grouped approximately in the $S = 0.1$–$0.2$ band of Strouhal numbers although the total spread in the values of $\alpha_m/\alpha_0$ occupies a rather large band of values $S = 0.075$–$0.6$.

The experimental results obtained permit the assumption that the root part of a nonisothermal axisymmetric subsonic jet is most responsive to the effect of acoustic, pure tone perturbations in the $S = 0.1$–$0.2$ range of Strouhal numbers.

It is interesting that the $S = 0.1$–$0.2$ range of Strouhal numbers disclosed is "inscribed" sufficiently well in the band determined in the theory of vortex sound by the relationship

$$0.14 \leqslant fD/V_\infty \leqslant 0.27$$

where D is the cylinder diameter, $f$ is the oscillation frequency, and $V_\infty$ is the free stream velocity.

This relationship determines the range of Strouhal numbers characterized by the fact that periodic disruption of the Benard–Karman vortices is observed in the free flow of a stationary air stream from the leeward side over cylindrical bodies in a broad range of Reynolds number variation. This same Strouhal number range also includes the wind resonance mode at which the frequency $f$ of Benard–Karman vortex disruption, which satisfies the relation $S = 0.2$ in the case of a cylinder, agrees with the frequency of free oscillations.

Therefore, the experimental investigations conducted showed that a nonisothermal, axisymmetric, subsonic turbulent jet possesses a quite definite selectivity relative to local acoustic oscillations, which is manifested externally as an increase in the magnitude of the jet's aperture angle (the fan-shaped expansion effect). It has been detected experimentally that the escape of a subsonic turbulent jet, on whose root part acoustic perturbations with intensity $I = 100$ dB $=$ const have been imposed, is most unstable in the $S = 0.1$–$0.2$ Strouhal number range. The change in the value of the aperture angle $\alpha_m/\alpha_0$ as a function of the Strouhal number S for fixed values of the parameter $u_0$ is complex and nonlinear.

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