8. M. A. Mikheev and I. M. Mikheeva, Principles of Heat Transfer [in Russian], Énergiya, Moscow (1973).
9. V. K. Shcherbakov and L. V. Kovalenko, Inzh.-Fiz. Zh., 31, No. 1 (1976).
10. L. A. Kozlova, Solution of Nonlinear Heat-Conduction Problems [in Russian], Naukova Dumka, Kiev (1976).
11. R. S. Guter and B. V. Ovchinskii, Principles of Numerical Analysis and Mathematical Processing of Experimental Data [in Russian], Nauka, Moscow (1970).

EXPERIMENTAL STUDY OF LAMINAR-TO-TURBULENT FLOW TRANSITION UNDER THE ACTION OF ACOUSTIC OSCILLATIONS

A. N. Shel'pyakov and G. P. Isupov

UDC 532.517

Experimental data are given on the effects of acoustic oscillations at frequencies up to 100 kHz on free laminar flow.

Acoustic agitation of a free laminar jet promotes the transition to turbulent flow for small Reynolds numbers Re [1]. When the acoustic source is removed, the jet returns to the laminar state.

The results of experimental investigations of the effect of acoustic oscillations on a free jet at a maximum frequency of 10 kHz are given in [1].

Here we discuss the results of experiments on the effect of acoustic oscillations on a free jet at frequencies up to 100 kHz.

The experiments were conducted with nozzle—nozzle jet elements having capillary diameters of 0.4 to 0.9 mm.

A typical curve of the pressure variation in the receptor duct as a function of the pressure in the injector duct is given in Fig. 1 (curve 2). The three main flow regimes (laminar, transition, and turbulent) correspond to the three intervals $0a$, ab, and bc of curve 2 in Fig. 1.

Theoretical and experimental studies of the laminar-to-turbulent transition [2] have shown that at the initial instant one or more small-amplitude oscillations arise in the flow in a single phase (Tollmien waves), subsequently evolving into more complex three-dimensional modes (Benney—Lin waves). These waves are broken up by vigorously growing small-scale pulsations (zone of secondary instability), which emerge as Emmons spots, continue to develop downstream, and induce turbulence throughout the entire flow.

A definite analogy exists between the development of acoustic emission from a jet and the transition of the latter from laminar to turbulent flow.

A pure laminar jet (lower half of interval $0a$) does not emit sound. As the injection pressure is increased (toward the end of interval $0a$) the jet begins to emit sound with a distinct single frequency (in our situation 5.3 kHz). A further increase in the injection pressure (interval ab) causes an increase in the total noise level of the jet, and the 5.3-kHz discrete component vanishes. We measured the acoustic characteristics of the jet with a microphone and analyzed them on the screen of an S1-19B oscilloscope.

The action of acoustic waves emitted by a jet on the flow regime of the latter is confirmed by the experiment described below. The objective of the experimental was to determine the acoustic emission component exerting the greatest influence on the evolution from laminar to turbulent flow.

The experimental arrangement is shown schematically in the inset of Fig. 1. It consists of the capillaries separated by a distance l. One capillary is the injector, and the other the receptor. A reflecting surface in the form of an aluminum plate with an area of 55 × 25 mm^2, thickness of 1 mm, and microroughness height $R_z = 3.2$ is set up at a distance L from the common axis of the capillaries. The experimental results are represented by curves 1 and 3 in Fig. 1 and the curve in Fig. 2.

Votkinsk Branch, Izhevsk Mechanics Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 35, No. 3, pp. 410-414, September, 1978. Original article submitted July 21, 1977.

0022-0841/78/3503-1026$07.50

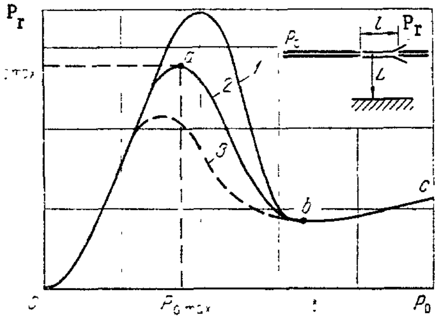

Fig. 1

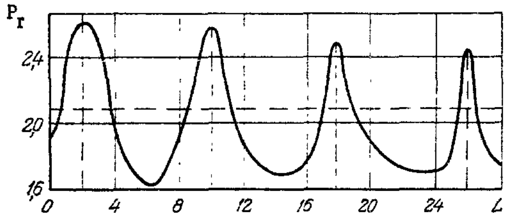

Fig. 2

Fig. 1. Typical curve of pressure in the receptor capillary versus pressure in the injector capillary; 1) L = 2, 10, 18 mm; 2) without reflecting surface; 3) L = 6, 14, 22 mm.

Fig. 2. Pressure P_r (kPa) in receptor capillary versus distance L (mm) of reflecting surface from the jet axis; d = 0.76 mm, l = 10 mm.

In the laminar regime the reflecting surface does not have any effect on the nature of the flow. If the injection pressure is increased until the flow corresponds to the beginning of the transition interval *a*b, the distance at which the reflecting surface is situated determines the type of flow.

The stability of laminar flow increases (curve 1 in Fig. 1) or decreases (curve 3) as the reflecting surface is moved further or closer to the jet. The variation of the pressure in the receptor capillary as a function of the distance L of the reflecting surface from the jet is shown in Fig. 2 (the horizontal dashed line gives the pressure $P_{r\text{-max}} = 20 \cdot 10^2$ Pa without the reflector in the vicinity of the flow).

The alternation of laminar and turbulent regimes (crests and troughs of the curve in Fig. 2) indicates interaction of the acoustic waves emitted by the jet with the reflected waves. The wavelength of the acoustic oscillations responsible for variation of the flow regime is equal to 16 mm, corresponding to a frequency of 21.2 kHz. Especially noteworthy is the fact that his frequency is a multiple of the previously generated frequency of 5.3 kHz. The distinct relationship between the initial disturbances and the geometry of the bodies surrounding the flow enable us to account for the diversity of laminar-to-turbulent transition forms observed by many researchers. Thus, in order to compare the numerous experimental data pertaining to the initial stage of evolution from laminar to turbulent flow it is necessary to have acoustic as well as hydrodynamic similarity, along with similarity of the initial disturbances (the initial turbulence factor) [2].

The mechanism of interaction of acoustic emission with a jet is portrayed as follows. The initial segment of the jet emits acoustic waves in the form of a narrow frequency spectrum, which propagate into the surrounding space, reaching the surface and being reflected from it. If the disturbances existing in the flow and reflected from the surface are in phase, the wave energy is additive, and the jet breaks up; if they are in antiphase, the development of the disturbances is self-sustaining.

As the jet flows from the injector to the receptor capillary the number of harmonics in the jet increases, their frequencies both increasing and decreasing. Small-scale disturbances have the dominant influence on breakup of the jet. The mechanism of interaction of small-scale disturbances is demonstrated in [3]. The interaction condition stipulates equality between the phase velocity of large-scale disturbances and the group velocity of small-scale disturbances.

For a more detailed analysis of the influence of acoustic oscillations on the laminar-to-turbulent transition we subjected the jet between the capillaries to the action of acoustic oscillations, varying their frequency from 0 to 100 kHz. The choice of a free jet as the object for investigation of the phenomenon was dictated by the need to impart a certain "purity" to the experiment. The experimental arrangement eliminated the influence of the microgeometry of any flow–obstacle flow surface as is usually experienced in the case of a boundary layer, to which the majority of the data on laminar-to-turbulent flow transition refers. For the same reason we used glass capillaries to minimize surface roughness. The acoustic source was a barium titanate piezoelectric crystal, to the faceplates of which was applied an alternating voltage from an oscillator. The generated frequency was varied smoothly at a definite rate by means of an electric motor, whose shaft was coupled to the tuning knob of the oscillator. The process was recorded on an N-700 loop oscillograph.

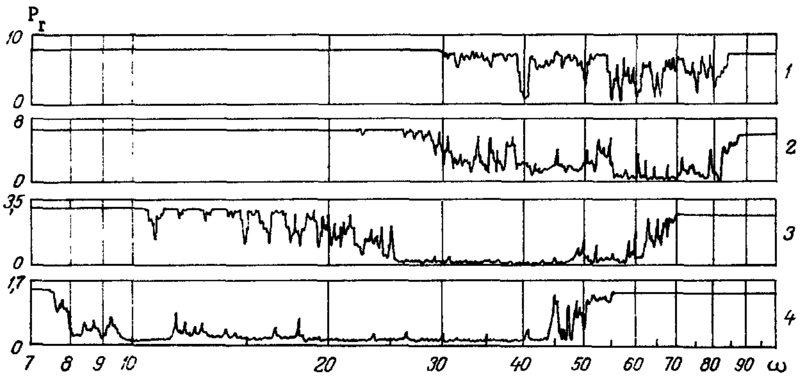

Fig. 3. Typical oscillogram of the action of acoustic oscillations on the turbulence promotion of a laminary jet, d = 0.4 mm, ω in kHz. 1) l = 6 mm, $P_0 = P_{0max} = 3.15 \cdot 10^4$ Pa; 2) 8 mm, $2.32 \cdot 10^4$ Pa; 3) 12 mm, $2.05 \cdot 10^4$ Pa; 4) 18 mm, $1.6 \cdot 10^4$ Pa.

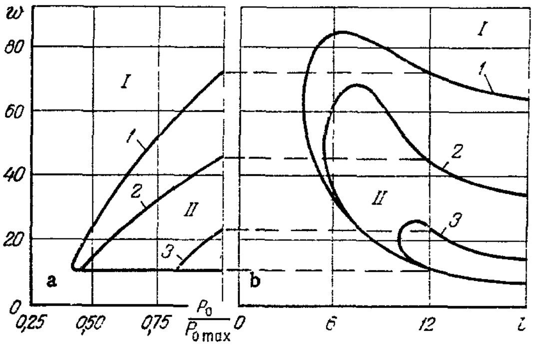

Fig. 4. Influence of l, P_0, and d on the spectrum of acoustic oscillations promoting jet turbulence. I) stability zone; II) instability zone; a) influence of injection pressure for l = 12 mm; b) influence of injector–receptor capillary spacing for $P_0 = P_{0max}$; 1) d = 0.40 mm; 2) 0.75; 3) 0.90.

The pressure in the receptor capillary was measured by means of a low-pressure strain gauge. The signal from the latter was amplified by a TA-5 strain-amplification station. Typical oscillograms are shown in Fig. 3. It was found that a laminar jet reacts to acoustic oscillations having a definite frequency spectrum, which depends on the values of the variables d, P_0, and l (Fig. 4). These variables can be grouped into two dimensionless criteria: Re and St.

With an increase in the spacing l the initial frequency of the spectrum shifts toward lower frequencies. An increase in the injection pressure, on the other hand, broadens the spectrum toward the high-frequency end. A decrease in the jet diameter also broadens the spectrum toward higher frequencies. The experimental data in Fig. 4 are presented in the same coordinates as those used for the actual experiment.

The use of the dimensionless criteria Re and St in the given case does not add any qualitatively new relations.

Thus, the experiments described here exhibit the appreciable influence of acoustic oscillations on the flow regime in the transition zone, providing a means of explanation of the diversity of results obtained by different researchers. Besides the initial turbulence factor, it is also necessary to take account of acoustic disturbance of the flow in the analysis of the transition zone. Moreover, by irradiating a flow with acoustic waves having definite parameters it is possible to exercise remote control over the laminar-to-turbulent flow transition.

NOTATION

P_0	is the injection pressure in injector capillary;
P_r	is the pressure at exit from receptor capillary;
$P_{0\,max}$	is the pressure in injector capillary with jet at the stability threshold;
P_{r-max}	is the pressure in receptor capillary with jet at the stability threshold;
l	is the distance between orifices of injector and receptor capillaries;
L	is the distance from capillary axis to reflecting surface;
d	is the inside diameter of capillary;
ω	is the acoustic frequency;
$Re = ud/\nu$	is the Reynolds number;
u	is the average flow velocity;
ν	is the kinematic viscosity;
$St = u/\omega l$	is the Strouhal number.

LITERATURE CITED

1. V. N. Dmitriev and V. G. Gradetskii, Fundamentals of Pneumatic Automation [in Russian], Mashinostroenie, Moscow (1971).
2. V. N. Zhigulev, A. I. Kirkinskii, V. N. Sidorenko, and A. M. Tumilin, "Mechanism of secondary instability and its role in the process of inception of turbulence," in: Aeromechanics [in Russian], Nauka, Moscow (1976).
3. M. T. Landahl, "Wave mechanics of breakdown," J. Fluid Mech., 52, No. 4 (1972).

FRICTION AND THE VELOCITY AND GAS-CONTENT PROFILES OF A TURBULENT GAS – LIQUID FLOW

A. V. Gorin

UDC 532.529.5

The limiting relative friction law is used to derive analytical expressions for the frictional stress as well as the velocity and gas-content distributions in the cross section of a boundary layer and a pipe.

Only a limited number of theoretical papers to date has any attempt been made to solve the problem of calculating the hydrodynamic characteristics associated with the turbulent flow of gas–liquid mixtures. In the majority of those papers the two-phase system is regarded as a locally homogeneous medium amenable to the methods and assumptions commonly used in the theory of single-phase turbulent flows. For example, Bankoff [1] postulates that the tangential stress is uniform throughout the channel cross section and the mixing length is the same as for single-phase turbulent flow. Brown and Kranich [2] use a logarithmic distribution function for the velocity of the mixture in the bubble-flow regime, neglecting the relative velocity between the phases. Beattie [3] treats the bubbles as cavities distributed in proportion to the velocity distribution of the liquid and adopts the same assumptions as in [1]. Levy [4] has derived distributions of the velocity and density of the mixture and the pressure drop on the basis of Van Driest's modification of mixing-length theory. Here the turbulent constants are considered to be the same as for single-phase liquid flow. Sato and Sekoguchi [5] regard the bubbles as cavities, the presence of which has the effect of creating fluctuations of the liquid velocity (over and above the independently existing single-phase turbulent fluctuations of the liquid velocity) due to flow around bubbles. This process induces additional turbulent stresses. The bubble function is considered to be a given quantity. Kashcheev and Muranov [6] have calculated the velocity profile of a mixture for annular-mist flow, replacing the two-phase core by a homogeneous flow and invoking the basic assumptions of semi-empirical turbulence theories.

The fundamental problem that arises in the realization of a locally homogeneous model is whether or not it is justified to use the turbulence constants for single-phase flow. Tong [7], for example, concludes on the

---

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 35, No. 3, pp. 415-423, September, 1978. Original article submitted June 27, 1977.