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GENERATION AND DAMPING OF FLOW OSCILLATIONS IN THE REGION OF A JOINT BETWEEN A PIPELINE AND A BLIND BRANCH

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We consider the problem of self-excitation of oscillations in the pipes of main gas-compressor stations. We present results of model investigations of intense narrow-band oscillations of pressure and velocity in a gas flow, which are due to the occurrence of instability and the formation of a self-oscillating system in the zone of a joint between a pipeline and a blind branch-resonator. The possibility of prevention or attenuation of self-oscillations is indicated.

In the course of investigations carried out at various gas-compressor stations, pressure oscillations of a resonance nature have been systematically detected in flows in pipelines of the framework, which present a real hazard to the integrity of structures. The gas flow velocities in 1-m-diameter pipes were equal in this case to 11-17 m/sec, and the frequencies of narrow-band oscillations were equal in some cases to 8-10 Hz and in other to 175-180 Hz, depending on the dimensions of the resonators. Both the former and the latter were not multiples of the rotation frequency of the supercharger of 16-25 MW power. The source of excitation of the intense oscillations considered was located in the region of the joint between a pipe-bellmouth and a blind branch serving for some purpose, for example, a manhole of diameter 500 mm or a pipe of diameter 700 mm with a closed cock located at some distance from the entrance. In both cases the angle of the cutting-in of the line ends was 90°. One might have assumed that this self-excitation of pressure oscillations is a well-known result of a stream flowing past a surface with a recess-resonator of one configuration or another [1].

Hypothetically it is assumed [1] that in the case considered a self-oscillating system results from the appearance of hydrodynamic waves of instability in a shear flow between the edges of the recess and acoustic perturbations, initiated by these waves, that realize feedback. This concept is confirmed indirectly by the existence of regions of instability in the plane of the parameters Sh number – Re number or Sh number – M number.

The dimensionless combinations $f_b d_{\rm br}/V_{\rm m} = {\rm Sh}$, $V_{\rm m} d_{\rm bel}/\nu = {\rm Re}$, and $V_{\rm m}/a = {\rm M}$ involve the maximum velocity $V_{\rm m}$, for example, on the axis of the bellmouth or at the outer edge of the shear flow, the frequency of intense self-oscillations f_b, the diameter $d_{\rm br}$ of the blind branch joined with the bellmouth of diameter $d_{\rm bel}$, the kinetic coefficient of gas viscosity ν, and the speed of sound propagation in the flow a. Results of direct investigations of the field of oscillations in a shear flow in the zone of the indicated junction of pipes are practically unavailable, although they are essential for the formation of a physical model of the processes discussed and for practical applications of this model. In particular, the phenomenon of the experimentally revealed absence of correspondence of the depth of the blind branch to the quarter wavelength of sound in the case of distinctly resonance oscillations stands in need of explanation. Therefore the aim of the present investigation is to obtain a definite idea about the structure of the shear flow in the region where there is a recess in the surface.

In setting up the investigations it was assumed first that the development of the waves of instability and the vortices in the zone of the junction, all other conditions being equal, depends crucially on the transverse velocity gradient and the wall friction τ just ahead of the recess. Second, it was assumed that fine-scale stochastic oscillations in the shear flow are of secondary importance in the formation of large-scale hydrodynamic perturbations in the

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TABLE 1. Coefficient of Friction on the Wall Upstream of a Blind Branch in Different Regimes of Flow

x_{noz}, mm	−4			−2				
$Re \cdot 10^{-5}$	1.06	1.58	3.00	1.10	1.61	2.18	2.54	4.03
$\tau_l \cdot 10^3$	1.29	1.11	0.895	2.28	1.79	1.72	1.73	1.86

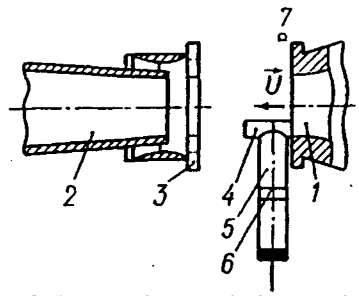


Fig. 1. Working section of the wind tunnel: 1) nozzle, 2) diverging segment, 3) honeycomb panel, 4) model of a fragment of the pipe-bellmouth surface, 5) blind branch, 6) insert, 7) microphone.

zone considered. Therefore it was deemed possible to carry out experiments on models not only in a stabilized turbulent flow but also in a flow with incomplete evolution of the velocity profile, remembering that the quantity $\tau_l = \tau/\rho V_m^2$ is both an overall and a local characteristic of the flow. Checking of the effectiveness of this approach is also an objective of this research.

1. To investigate self-oscillating processes we used an open-throat wind tunnel (WT) with an exit diameter of the nozzle d_{noz}=150 mm. Initially the boundary layer at the exit of the nozzle was virtually laminar due to 8-fold compression of the flow. To change the mode of flow in the boundary layer and increase the wall friction, a turbulizer made of a 1-mm-diameter wire was installed at a distance of 80 mm upstream from the exit of the nozzle. The parameters of the laminar and turbulent boundary layers were measured at distances x_{noz} = −4 and −2 mm, respectively, upstream from the tip of the nozzle. The data given in Table 1 indicate that it was possible to change the value of τ_l within rather wide limits in this way in front of the models in the working section of the tunnel and, in particular, to obtain values of τ_l close to the actual ones.

One of the models installed in the working section of the WT was a fragment of a cylindrical surface, which on a length of 110 mm was an extension of the nozzle wall in the sector of a circle extended 120° over the azimuth (Fig. 1). The second model was a portion of the bellmouth 255 mm in length, which, when installed in the WT, became a cylindrical closed portion of the latter of inner diameter 150 mm. Blind branches of inner diameters 53, 110, and 128 mm were installed in the full model of the portion of the bellmouth, and one of diameter 53 mm was installed on the fragment. The leading edges of these branches were located at a distance of 14 mm from the end of the nozzle, which was cylindrical at the exit. The depth t of the blind branch was varied by displacing an insert in it. When the working section of the tunnel was kept open, a honeycomb panel was placed in front of the inlet to the diverging segment to prevent self-oscillations in the channel of the wind tunnel per se [2].

The model of the fragment of the bellmouth surface with a blind branch on it is made from transparent Plexiglas and glass in order to visualize the flow. The model was also intended for carrying out thermometric measurements in the flow and comparing self-oscillations in regions with different boundary conditions on the fragment and on the full model of the portion of the bellmouth with a branch.

It should be emphasized that in this installation attention was paid mainly to modeling the near-wall region of the flow, rather than the entire profile of velocities in the bellmouth. In particular, the thickness of the shear-flow layer at the inlet to the model did not exceed 8 mm in all cases. But here the possibility of varying the wall friction within wide limits upstream of the joint between the surfaces of the bellmouth and the blind branch was ensured. The velocity in the flow core at the exit from the nozzle of the tunnel was varied in the experiments from 10 to 50 m/sec, and the Reynolds numbers were equal to $(1-5) \cdot 10^5$. The joints of the surfaces of the bellmouth and the branch were not rounded on purpose to have rather distinct manifestations of self-oscillations.

Oscillations of the pressure p, the velocity u, and time-averaged values of the velocity U were measured by a 00026 sound level meter with a one-inch MK102/MV102RFT condenser microphone, a 55D05 constant-temperature thermoanemometer, a 55D35 millivoltmeter, a unifilar heat probe with a 3-mm-diameter case made by DISA Elektronik, a Robotron 01025 narrow-band spectral analyzer with a 02013RFT recorder, a C1-107 multimeter, and a traverse mechanism to displace the heat probe in the flow field investigated. Pulsations were analyzed in the range of frequencies f = 2–2000 Hz, which accounted for the main part of the energy of the processes considered, with a 3% transmission band and a 3-min time of analysis.

In thermometric measurements the longitudinal axis x was assumed to be directed parallel to the axis of the open working portion of the WT from the forward point of the joint between the bellmouth and the branch downstream, the y axis was assumed to be directed from the surface of the bellmouth along the internal normal to it in the vertical plane of symmetry of the model of the pipe fragment, and the z axis to be directed along the normal to the other two in a right-handed coordinate system. Below, the values of the coordinates are referred to the diameter of the blind branch d_{br}.

In all the experiments the microphone was installed outside the flow, and in investigations on the model of the fragment it was installed on the side of the working section of the WT opposite the fragment. The longitudinal axis of the microphone was parallel to the axis of the working section of the tunnel and at a distance of 190 mm from it, and its guard mesh was located 30 mm downstream of the end of the nozzle. The results of the measurements by the microphone at a single indicated cross section made it possible to obtain a rather complete fundamental idea about the processes occurring.

In the investigated range of velocities control measurements were made on the pressure fluctuations generated by the wind tunnel itself with the models of the fragment and the portion of the bellmouth without a blind branch, as well as with a blind branch, when, with the insert being adequately positioned in the branch, self-oscillations were not initiated in the flow. In all these cases virtually a wide-band spectrum of pressure oscillations $L(f)$ and a relatively small overall level of them L_Σ were observed. Due to the differences in the character of the flow in the partial and the full model of the bellmouth and due to the decrease in the level of oscillations owing to the wall, the values of L_Σ in the cases compared differed by about 20 dB.

2. The simplest visualization of the flow by silk threads fixed on the probe confirmed the validity of the means selected for reproducing in the main the natural processes on the model of the fragment of the bellmouth with a blind branch. It is found that the flow past the portion of the surface that simulates the wall of the bellmouth corresponds to the motion of the actual flow in this region. Here, one did not observe any washes of the flow in the vicinity of the blind branch that would be attributable to the dimensions of the model. No separations on the fragment of the surface were seen downstream of the blind branch.

Moreover, visualization made it possible to determine the dimensions of the region where sufficiently full information about the flow can be obtained in measuring the time-averaged and oscillating components U and u of the instantaneous value of the longitudinal velocity component by a unifilar heat probe. In visualization one could clearly see the change in the flow vorticity at the place where a bunch of silk threads is located in it in the case of the occurrence of self-oscillations. Below the region mentioned, at the place where thermoanemometric measurements were made, the flow in the blind branch had a rather complex vortical structure that also underwent visible changes with the appearance of self-oscillations.

The most detailed comparative experiments were conducted for the case where the relative diameter d_{br}/d_{bel} was not large, namely 0.353. Below we will show that the trends revealed in this case are rather general. The aforementioned blind branch was installed on the fragment of the model of the bellmouth in the presence and absence of a turbulizer on the wall of the nozzle and on the full model of the portion of the bellmouth in the presence and absence of a turbulizer at the exit from the nozzle.

A comparison of the spectra determined for the fragment of the model of the bellmouth indicates a dependence of the narrow-band oscillations of pressure in the flow on the transverse velocity gradient in the wall flow upstream of the joint between the bellmouth and the branch. Thus, at the same depth of the latter t/d_{bel} = 5.57 and nearly the same Reynolds numbers Re = $(1.16-1.18) \cdot 10^5$ for the larger value $\tau_1 = 2.15 \cdot 10^{-3}$ there are somewhat lower frequencies of self-oscillations and Strouhal numbers Sh = 0.945 and levels of pressure oscillations

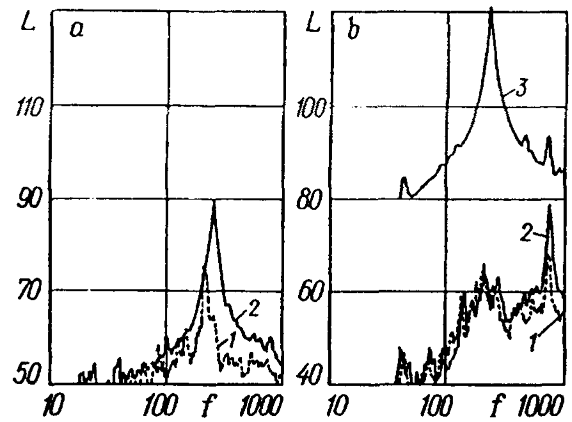


Fig. 2. Spectra of pressure oscillations $L(f)$ measured (a) on the model of a fragment of the bellmouth surface with a blind branch at $t/d_{br} = 5.57$ [1) Re $= 1.18 \cdot 10^5$, $\tau_l = 2.15 \cdot 10^{-3}$; 2) $1.16 \cdot 10^5$ and $1.25 \cdot 10^{-3}$] and (b) at $t/d_{br} = 5.57$ on a blind branch on the model of a portion of the bellmouth [1) Re $= 3.92 \cdot 10^5$, $\tau_l = 1.92 \cdot 10^{-3}$; 2) $3.95 \cdot 10^5$ and $0.86 \cdot 10^{-3}$] and a blind branch in the model of a fragment of the bellmouth surface [3) Re $= 3.87 \cdot 10^5$, $\tau_l = 1.92 \cdot 10^{-3}$]. L, dB.

in the section of measurements (Fig. 2a, spectrum 1) than the same parameters at the smaller value $\tau_l = 1.25 \cdot 10^{-3}$ (Fig. 2a, spectrum 2, Sh = 1.17). It should be noted that in the measurements the relative depth tf_b/a was equal to 0.204 for spectrum 1 and to 0.230 for spectrum 2.

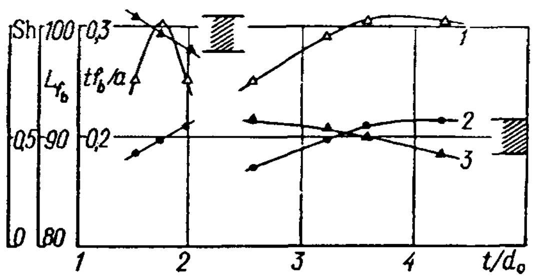
A similar regularity was observed in the case where a blind branch was installed in the full model of the bellmouth portion (Fig. 2b, spectrum 1, Sh = 0.968, $tf_b/a = 0.615$; spectrum 2, Sh = 1.02, $tf_b/a = 0.644$).

The differences noted are not large on the whole and nevertheless the data obtained in the cases compared turn out to lie within the same limits of each of the instability regions in the plane of the parameters Sh$-\tau_l$. As expected, the differences in the boundary conditions on the boundary of the region of the flow within which there is the joint between the bellmouth and the branch influence the parameters of the self-oscillations. For example, in the presence of a turbulizer on the wall of the nozzle, for Re $= (3.87-3.92) \cdot 10^5$, $\tau_l = 1.92 \cdot 10^{-3}$, and $t/d_{br} = 5.57$ in the case where the branch is installed on the fragment and in the full model of the bellmouth portion (spectra 3 and 1 in Fig. 2b) the Sh numbers of the self-oscillations are equal respectively to 0.327 and 0.968, and the values $tf_b/a = 0.212$ and 0.615. The Sh numbers corresponding to the same τ_l but on the whole different flows, may turn out, with the other parameters nearly the same, to be both in different regions of instability and in one of these regions in the plane of the quantities Sh$-\tau_l$.

On the fragment of the model of the bellmouth with a blind branch of diameter 53 mm in the presence of a turbulizer within the nozzle we carried out measurements of pressure oscillations in the case of a systematic change in the depth t. The combined results of these measurements for a flow velocity $V_m = 40.4$ m/sec are presented in Fig. 3. The character of the dependences presented in the figure is rather typical of the blind branches investigated in the present work. In carrying out the experiments the changes in the amplitude and frequency of the self-oscillations with displacement of the insert in the branch could be watched directly on the screen of an oscillograph.

From an analysis of the combination of the experiments listed it follows that the problem considered must be solved in the same way as was done in [3] in the problem of interrelated hydrodynamic and acoustic modes of oscillations.

With account for the results obtained in the experiments at $d_{br}/d_{bel} = 0.353$, the oscillations of pressure for two other values $d_{br}/d_{bel} = 0.733$ and 0.853 were determined only for the full model of the bellmouth portion with a blind branch without a turbulizer within the nozzle, which ensured the closest approximation to natural circumstances. From the spectra of the pressure oscillations obtained here for branches of diameters 110 and 128 mm the Sh numbers of the self-oscillations were calculated, which corresponded to definite values of τ_l. The data



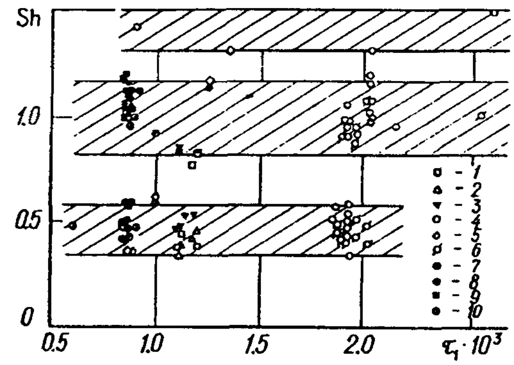


Fig. 3. Dependences of the level of the narrow-band component L_{f_b}, dB (1), the value of t_{f_b}/a (2), and the Strouhal number Sh (3) on the relative depth of the blind branch t/d_{br}.

Fig. 4. Dependence of the Strouhal number of the self-oscillations on the dimensionless friction on the wall upstream of a blind branch τ_1 under different experimental conditions (Table 2).

TABLE 2. Characteristics of the Experimental Conditions

Number of the experimental point	d_{br}, mm	t, mm	Installation	Type of model	Turbulizer inside the nozzle
1	60	505	Rig with pipelines		
2	60	120	Same		
3	63	120	Same		
4	53	Var	WT	Fragment of the bellmouth	With
5	53	295	"	Fragment of the bellmouth with a screen	Without
6	53	Var	"	Full model	With
7	53	"	"	"	Without
8	110	"		"	"
9	128	"		"	"
10	700		Actual circumstances		

of all the experiments listed above are presented in Fig. 4; this figure also contains results (obtained after all the necessary conversions) of experiments carried out by the present authors on a rig on a model of a pipeline with a stabilized turbulent flow and blind branches and also full-scale investigations. Table 2 indicates the conditions under which the experimental points indicated by numbers in Fig. 4 were obtained.

The experimental data presented in Fig. 4 indicate the existence of rather vast regions of instability in the plane of the parameters Sh$-\tau_1$; it is precisely this instability that gives rise to self-oscillations. Evidently, it is admissible to assume that the limiting values of the Sh number, characteristic of each of these regions, are constant in a wide range of values of τ_1 and refer equally to different ratios d_{br}/d_{bel} and t/d_{br}, at least in the ranges investigated.

Two circumstances are especially noteworthy. First, irrespective of the absolute values of the diameter and depth of the blind branch-resonator the self-oscillations were usually most distinct when t was close to a quarter or three-quarters of the acoustic wavelength $\lambda_a = a/f_b$. Second, no matter how great the scatter of the values of the Sh number may be, they definitely gravitate to the values 0.5, 1.0, and 1.5. In view of the latter, the Sh number must be expressed in a form that differs somewhat from the conventional one, namely Sh $= f_b d_{br}/V_m$ =

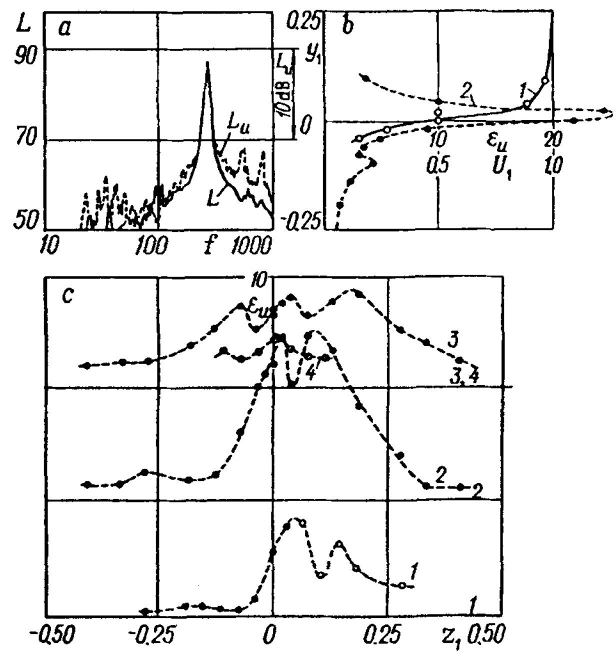


Fig. 5. (a) Spectra of oscillations of pressure $L(f)$ and velocity $L_u(f)$ (x_1 = 0.302, y_1 = 0.0189, z_1 = 0), (b) profiles of the velocity (1) and the intensity of the narrow-band component of the velocity oscillations (2) (Re = $1.27 \cdot 10^5$, t/d_{br} = 5.57, x_1 = 0.302, z_1 = 0), and (c) dependences of the intensity of the narrow-band component of the velocity oscillations ε_u (%) on the z_1 coordinate [Re = $1.26 \cdot 10^5$, t/d_{br} = 5.57, $y_1 \approx 0.015$, 1) x_1 = 0.113, 2) 0.302, 3) 0.679, 4) 0.962].

$(1/T)(d_{br}/V_m) = (d_{br}/\lambda_h)(V_h/V_m)$. Here λ_h and V_h are the wavelength and the velocity of propagation of the hydrodynamic perturbation in the zone of the junction of the bellmouth and the branch. When it is remembered that in the self-oscillations, for example, in the open working section (a recess) of wind tunnels $V_h/V_m \approx 0.5$ [4], it is logical to assume that d_{br}/λ_h = 1, 2, 3, ... when Sh = 0.5, 1.0, 1.5, ...

From this it follows that when the maximum velocity on the bellmouth axis under actual circumstances is known, it is possible to calculate approximately the frequencies of possible self-oscillations. Namely: $V_h \approx 0.5V_m$, $\lambda_h \approx d_{br}$, $f_b = V_h/\lambda_h \approx 0.5V_m/d_{br}$ when Sh = 0.5, $f_b = V_m/d_{br}$ when Sh = 1, ...

Using these equalities, it is possible to calculate how large the depth of the blind branch must be to avoid self-oscillations. However, this a method of preventing dangerous oscillations cannot be admitted one hundred percent reliable, in particular, because of the above-noted scatter in the values of the Sh number about the values 0.5, 1.0, etc. Therefore, to improve the effectiveness of these measures, one should use the method of reducing the scales of hydrodynamic structures that initiate intense narrow-band pressure oscillations.

It was found in full-scale investigations that it may happen that one blind branch on a pipe-bellmouth may not excite intense narrow-band oscillations of pressure in the flow. But if there turns out to be one more blind branch downstream in the framework of the compressor station, intense low-frequency self-oscillations may appear in pipelines. We managed to reproduce this situation in experiments. Hand in hand with this, one observes in experiments also the reverse effect of a decrease in the amplitude of self-oscillations in interaction of perturbations from two blind branches compared to those excited by one branch.

3. A detailed investigation of the structure of the flow in the joint between the bellmouth and the branch was carried out for three values of the Reynolds number and the relative depth of the branch. As an example of the results obtained in measurements in different cross sections Fig. 5a presents spectra of velocity and pressure oscillations in a self-oscillating regime appearing at Re = $1.26 \cdot 10^5$ and t/d_{br} = 5.57. Here $\varepsilon_u = \sqrt{\langle u_f^2 \rangle}/V_m$ = 24.5%, $\varepsilon_p = 2\sqrt{\langle p_f^2 \rangle}/\rho V_m^2$ = 0.406%, u_f and p_f are the narrow-band components of the spectra of velocity and static-pressure oscillations at the frequency of the self-oscillations.

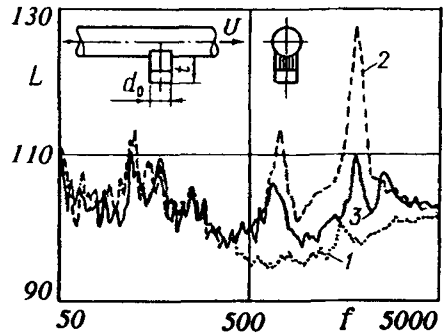


Fig. 6. Spectra of pressure oscillations $L(f)$ in a pipe-bellmouth without a blind branch (1), with a blind branch (2), and with a blind branch and longitudinal fins (3).

Estimates indicate that the level of the components observed at the frequency of the self-oscillations in the spectrum of velocity oscillations is attributable to hydrodynamic processes. The correspondence between the frequencies of intense narrow-band pressure oscillations in the near field and the velocity in the flow itself does not raise doubt about the interrelation between acoustic and hydrodynamic perturbations generated by the flow in the joint between the bellmouth and the blind branch.

Using the results of thermoanemometric measurements, we determined profiles of the time-averaged velocity U_1 (y_1, x_1 = const, z_1 = 0) and the intensity of narrow-band oscillations of velocity ε_u (y_1, x_1 = const, z_1 = 0) and dependences of ε_u (z_1, x_1 = const, y_1 = const), $U_1 = U/V_m$. Some of them are presented in Fig. 5b, c.

From the experimental data it follows that the greatest amplitude of the waves of instability corresponds to the layer of the shear flow developing downstream of the leading edge of the joint between the bellmouth and the blind branch where the velocity profiles $U_1(y_1)$ have an inflection point. The maximum levels of intensity of the oscillations are observed in the flow at a distance downstream of the front edge equal to approximately one-third of the diameter of the blind branch, at a distance of $(0.010-0.015)d_{br}$ from the generatrix of the bellmouth (Fig. 5c). As the instability waves are displaced downstream, they initiate similar oscillations in an increasingly thicker layer of the gas, but their amplitude decreases in this case, and this becomes especially noticeable in front of the rear edge of the junction of the two pipes. The results of the measurements, in particular, those presented in Fig. 5b, indicate that the effective length of a blind branch can be larger than the geometric one, since the hydrodynamic structures that initiate acoustic oscillations are partially immersed in the flow in the bellmouth.

Already at the inlet to the blind branch the field of oscillating velocities is inhomogeneous (Fig. 5c). It seems that the second, smaller, maximum on the $\varepsilon_u(y_1)$ profiles (Fig. 5b) is due to the formation of a vortex flow in the blind branch. This was also distinctly indicated by the results of flow visualization. It is evident, however, that the mechanism of self-oscillations is triggered and sustained precisely by hydrodynamic waves of instability in a shear flow at the junction of the blind branch with the bellmouth.

The data on the dimensions and character of the large-scale hydrodynamic structure that generates intense pressure oscillations made it possible also to find a method of their prevention or decrease to a safe level for the structures. On a special rig, which modeled the pipelines of a compressor station, at the junction of a bellmouth with a branch we installed several longitudinal fins orientated along the flow, which extended into the bellmouth and were partially sunk into the branch. They had to play a double role: on the one hand, to reduce the scale of the hydrodynamic structures that generated narrow-band oscillations of pressure and, on the other hand, by changing the wave numbers that corresponded to the z_1 coordinate, to cause a change in the entire spatial wave motion, in particular, in the frequency of the hydrodynamic oscillations, and to disturb the self-oscillating system. Actually, this was the way in which we managed to decrease considerably the intensity of narrow-band pressure oscillations.

Figure 6 presents spectra of pressure oscillations in a pipe-bellmouth without a branch 1, in a pipe with a blind branch ($t/d_{br} = 2$) 2, and in a pipe with the same branch but with five longitudinal fins 3. Since the hydraulic resistance of the longitudinal fins is insignificant, the indicated method of preventing self-oscillations is acceptable for actual use and, moreover, not just in the pipelines of the framework of compressor stations.

Thus, it was established by our investigations that the intense self-oscillations observed in a number of cases in the pipes of main gas-compressor stations are excited and sustained by instability waves in a shear flow in the region between the edges of the joint between a bellmouth and a blind branch. It was shown that their amplitude is greatest in the layer of the shear flow in the zone of the entrance into the blind branch, where the profiles of the time-averaged velocity have a point of inflection. In the plane of the parameters $Sh-\tau_1$ vast zones of instability are found that correspond to self-oscillating regimes at different relative diameters and depths of the blind branch. To prevent self-oscillations in the pipes of gas-compressor stations, it is suggested that the scales of the hydrodynamic structures at the entrance to a blind branch that initiate intense narrow-band pressure oscillations be changed. The results presented may turn out to be useful for the analysis of various aspects of the problem of self-excitation of intense oscillations in flow past surfaces with recesses.

NOTATION

U, time-averaged longitudinal velocity component; u, oscillating component of the longitudinal velocity component; L, level of oscillations; Re, Reynolds number; Sh, Strouhal number; M, Mach number; ε, intensity of oscillations; λ, wavelength. Subscripts: 1, dimensionless quantities; b, self-oscillation; u, velocity; p, pressure; f, frequency; bel, pipe-bellmouth; br, blind branch; n, nozzle of the wind tunnel; Σ, overall value; h, hydrodynamic perturbation; a, acoustic perturbation.

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