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EJECTION-INDUCED CHANGE IN THE STRUCTURE OF A TURBULENT WAKE

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The paper presents results of an experimental model investigation of the transformation of the velocity field behind a two-dimensional body under the influence of a jet emerging from a slot. Profiles of the mean velocity and the longitudinal and transverse components of the velocity are measured at a distance of up to 30 diameters from the body downstream. The jet was ejected through slots of different widths at a flow rate that ensures the establishment of the maximum bottom pressure.

Introduction. The magnitude of the bottom pressure of a body is determined by the conditions of formation of the flow that is immediately adjacent to the base of the body. The deficit of pressure in the wake region of a model (larger, the higher its base) depends on the size and intensity of the vortex formed behind the body as a result of separation of shear layers from the surface of the model [1]. The vortex is a source of rarefaction, and the closer it is to the model, the lower the pressure on the base, i.e., the higher the magnitude of its bottom resistance. The ejection of a jet from a slot made on the bottom of the model at relatively low flow rates causes an increase in the bottom pressure [2-5], which can naturally be related to the change in the dynamics of formation of a vortex. Earlier it was shown [5] that the maximum value of the bottom pressure depended on the width of an emerging jet, i.e., the structure of the flow behind the model in the case of emergence of wide and narrow jets has special features, the quantitative characteristics of which can be found by measuring the distributions of the mean velocity and the velocity fluctuations. Known investigations that establish the relationship between the parameters of an ejected jet and the dynamics of a wake flow are very few in number [6, 7]. The aim of the present work is a systematic investigation of the effect of a jet ejected through slots of different widths on the transformation of the turbulence characteristics of the flow behind the model. Since the width of the slot exerts an influence on the magnitude of the bottom pressure and the frequency of the shedding of shear layers in the absence of the emergence of a jet [5], it appears possible to obtain simultaneously data on the effect of the given parameter on the change in the velocity field behind the model.

Experiment. Investigations were carried out in an open-type wind tunnel [5]. A plane two-dimensional body with semicircular fore and blunt aft edges was installed at the beginning of the working section of the tunnel at a zero angle of attack to the free stream flow. The base of the model is formed by two identical rectangular blocks fixed to the upper and lower plates with a certain distance h between them that changes upon displacement of the blocks within the following range of values: $h/H = 0.02$ (model 1); 0.05 (2); 0.07 (3); 0.1 (4); 0.18 (5); 0.26 (6); 0.4 (7); 0.75 (8). A detailed description of the model is given in [5]. Measurements of the turbulence characteristics of the flow were made by means of an X-shaped probe connected to a Dantec thermoanemometer. The flow velocity in the tunnel was equal to 14 m/sec, which corresponded to a Reynolds number $\mathrm{Re}_H = 37{,}000$.

Profiles of the mean velocity and the velocity fluctuations were obtained in seven cross sections at a distance $x/H = 3-30$ from the base of the model. The investigations were carried out: 1) when there was no ejection of a jet and the parameter h/H was varied (the model in which the slot was sealed up with a film was considered to be the base model); 2) when a jet was ejected through a slot of various widths under the invariable condition that maximum bottom pressure was developed on the model base. By means of the procedure described in [5], the region of the flow that is directly adjacent to the body base was visualized for models with narrow ($h/H = 0.1$) and wide ($h/H = 0.4$) slots for various values of the ejection coefficient C_q.

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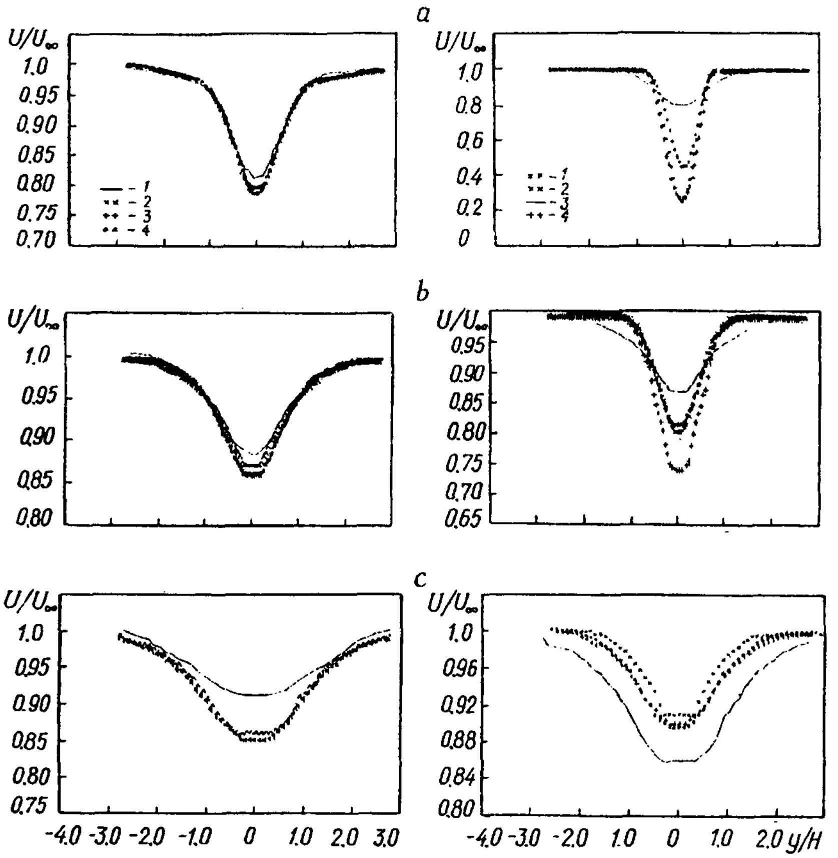


Fig. 1. Mean-velocity profiles in the wake behind a model with a slot of different widths [on the left: 1) $h/H = 0$, 2) 0.26, 3) 0.4, 4) 0.75] and behind a model with ejection of a jet [on the right: 1) model 6, 2) 7, 3) 8 ($C_q = 0$), 4) 8]: a) $x/H = 3$; b) $x/H = 10$; c) $x/H = 30$.

Results of the Investigations. *Transformation of the dynamic characteristics of the flow under the influence of a cavity made in the base of the model.* Earlier it was shown [8] that the frequency of vortex formation behind the model, characterized by the Strouhal number, changed under the influence of a cavity if the parameter $h/H > 0.1$. A change in the mean-velocity profile was also observed when $h/H > 0.1$. The velocity defect increased with increase in the relative width of the slot. The difference between the velocity defect on the axis of the wake behind a model with a slot in its base and the base model increased downstream (Fig. 1).

Compared with the base profile, the maximum longitudinal velocity fluctuations increased at a distance $x/H \leq 7$, and the transverse fluctuations increased up to a cross section $x/H \leq 20$ behind models with $h/H < 0.75$ (Fig. 2). The level of the fluctuations is higher, the narrower the slot. The distributions of the longitudinal fluctuations behind the model with the largest slot virtually coincided with similar distributions behind the base model at $x/H = 3$, and farther downstream their maximum became lower. For the transverse fluctuations correspondence with the base profile occurred up to $x/H = 10$, and upon displacement downstream the maximum increased. At a distance $x/H = 30$ the profiles of the fluctuations virtually did not differ from the base profiles.

The degree of degeneration of the mean-velocity defect on the wake axis decreased for models with a width of the slot $h/H > 0.1$ (Fig. 3). In the investigated range of distances the change in the defect was approximated by the power law $\Delta U \sim (x)^{-0.2}$. The width of the wake determined from the mean-velocity profile contracted more, the wider the slot in the model base. The law of change of this parameter, just as for the base model, obeyed a power law with an exponent $n = 0.5$. The laws of degeneration of the velocity fluctuations and expansion of the width did not undergo changes (Fig. 3). The width of the wake determined from profiles of the velocity fluctuations decreased with increase in the parameter h/H. The transverse fluctuations dropped twice as rapidly as the

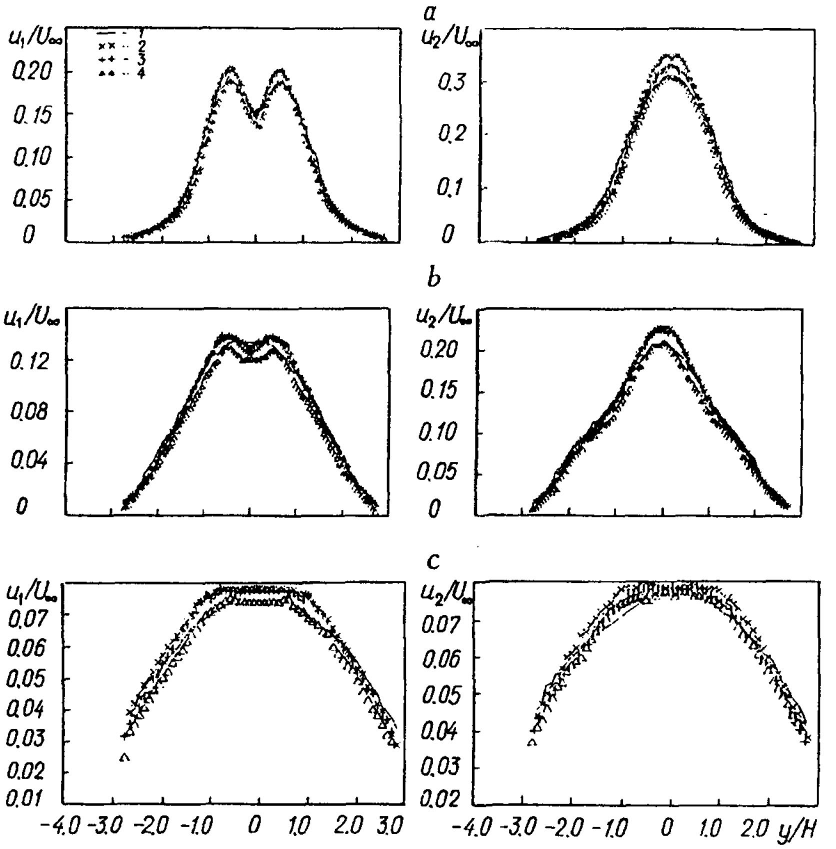


Fig. 2. Profiles of the longitudinal (on the left) and transverse (on the right) velocity fluctuations in the wake behind a model with a slot of different widths [1) $h/H = 0$, 2) 0.26, 3) 0.4, 4) 0.75]: a-c) same as in Fig. 1.

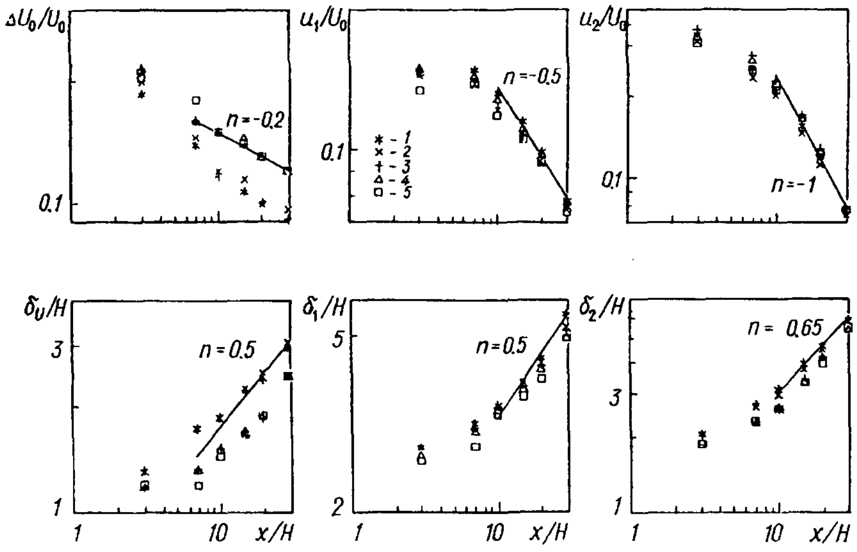


Fig. 3. Degeneration of the mean velocity defect, the velocity fluctuations, and the corresponding half-widths behind a model with a slot of different widths: 1) $h/H = 0$, 2)0.1, 3) 0.26, 4) 0.4, 5) 0.75.

longitudinal ones, i.e., the anisotropy of the flow typical of the base model was retained behind a model with a cavity in its base.

Effect of an ejected jet on the change in the turbulence characteristics of the wake. The defect of the mean velocity on the flow axis increased with the width of the jet (see Fig. 1). The difference in the value of ΔU behind

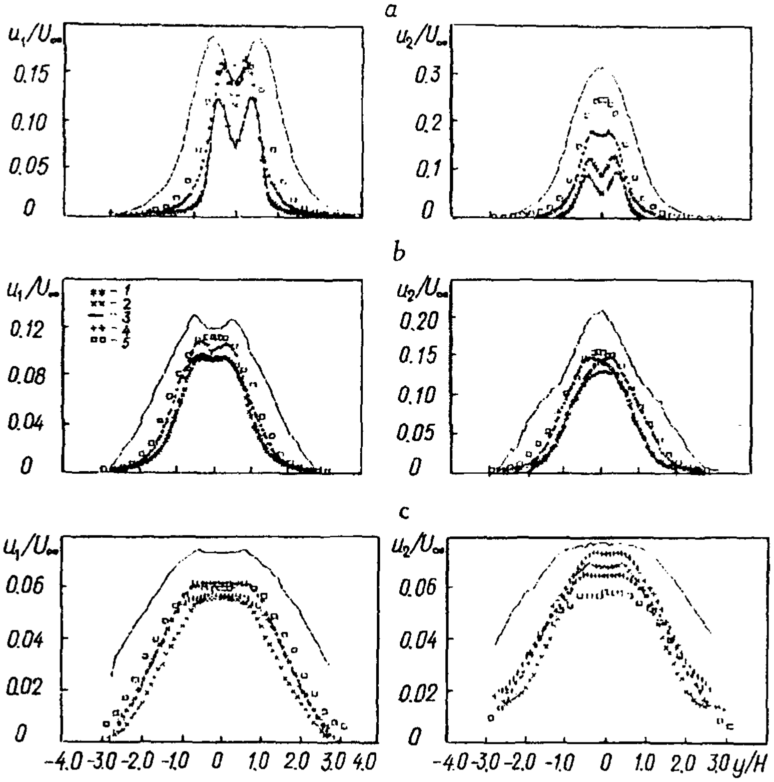


Fig. 4. Profiles of the longitudinal (on the left) and transverse (on the right) velocity fluctuations in the wake behind a model with jet ejection [1) model 6, 2) 7, 3) 8 ($C_q = 0$), 4) 8, 5) 4]: a-c) same as in Fig. 1.

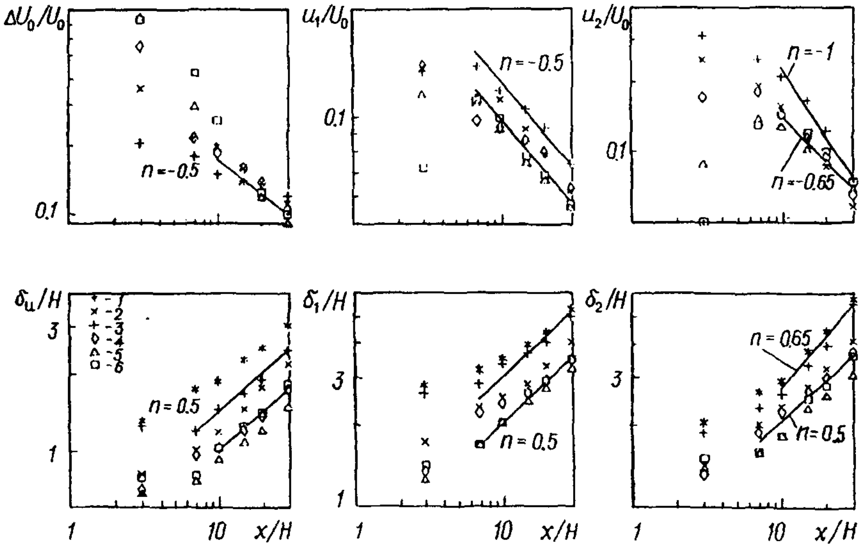
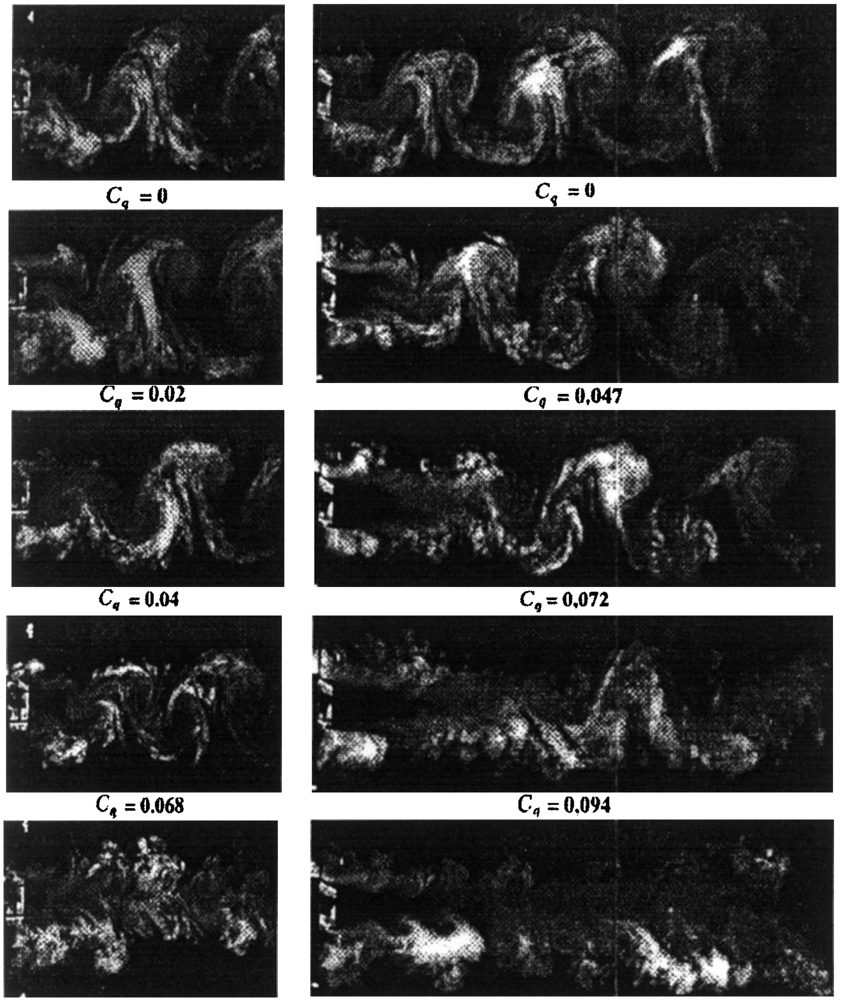


Fig. 5. Degeneration of the mean-velocity defect, the velocity fluctuations (above), and the corresponding half-widths of the wake behind a model with jet ejection (below): 1) model 4 ($C_q = 0$), 2) 4, 3) 8 ($C_q = 0$), 4) 6, 5) 7, 6) 8.

the base model and models with ejection decreased downstream. At a distance $x/H = 30$ the measured value of ΔU of the mean velocity is smaller than behind the same model without ejection ($h/H = 0.75$) but differs little from the velocity defect behind the base model.

Under the effect of a jet, the profiles of the fluctuations became narrower and their level decreased (Fig. 4). Behind models with $h/H < 0.1$ the fluctuations decreased steadily downstream [9]. The values of the



$C_q = 0$ $C_q = 0$

$C_q = 0.02$ $C_q = 0{,}047$

$C_q = 0.04$ $C_q = 0{,}072$

$C_q = 0.068$ $C_q = 0{,}094$

$C_q = 0.13$ $C_q = 0.142$

Fig. 6. Visualization of the near region of the wake flow behind model 4 ($h/H = 0.1$) on the left and behind model 7 ($h/H = 0.4$) on the right.

longitudinal fluctuations were lower than the transverse ones up to the cross section $x/H = 20$, where they virtually became the same. Behind model 7 ($h/H = 0.4$) the longitudinal fluctuations decreased steadily downstream, but the transverse fluctuations increased from the cross section $x/H = 3$ to the cross section $x/H = 7$ before they began to decrease. The difference between the maximum values of the longitudinal and transverse fluctuations was ~10% at $x/H = 30$. Behind model 8 ($h/H = 0.75$) the longitudinal and transverse fluctuations increased from the cross section $x/H = 3$ downstream: the former up to the cross section $x/H = 7$ and the latter up to the cross section $x/H = 10$; thereafter their values decreased. For models 7, 8 the level of the longitudinal fluctuations at the cross section $x/H = 3$ was higher than the level of the transverse fluctuations by about 24%. At a distance $x/H = 30$ the same value characterized the excess of the transverse fluctuations over the longitudinal ones.

The degeneration of the mean-velocity defect on the wake axis behind models with $h/H > 0.1$ was described by a power law with an exponent $n = -0.5$, which was typical of the self-similar region of the flow (Fig. 5). The width of the wake determined from the mean-velocity profile also increased in accordance with the self-similar law $n = 0.5$. The wake behind a model is narrower, the wider the jet emerging from the slot. It should be noted that the degeneration of the velocity defect behind a model with a jet ejected through a slot with $h/H = 0.02-0.07$ has been described by a power law with an exponent $n = -0.4$ [9].

The law of degeneration of the longitudinal and transverse fluctuations behind models with $h/H \le 0.1$ did not differ from the corresponding law behind the base model [9]. As the width of the jet increased ($h/H > 0.1$), the law of degeneration of the longitudinal fluctuations was retained, but the rate of degeneration of the transverse fluctuations decreased and approached that of the longitudinal fluctuations. The width of the profiles of the fluctuations was narrower, the wider the jet ejected. The widening of the wake downstream was described by a power law with an exponent $n = 0.5$ for both the longitudinal and transverse fluctuations.

Visualization of the flow showed differences in the dynamics of the formation of a vortex wake under the influence of emergence of a medium through narrow ($h/H = 0.1$) and wide ($h/H = 0.4$) slots (Fig. 6). The length of the shear layers discharged from the surface of the model increased insignificantly up to formation of the first vortex upon ejection of a narrow jet. The coordinate of the vortex center moved not farther than $1.5H$ downstream for $C_q = 0.068$ ($h/H = 0.1$). Under the influence of a wide jet, the shear layers were lengthened before being convoluted into a vortex, and the elongation was greater, the larger the magnitude of the flow-rate coefficient. For the value $C_q = 0.094$, when the maximum pressure was established on the base of the model with $h/H = 0.4$, the coordinate of the center of the first vortex moved a distance of about $7H$ downstream. Beginning from the flow rate $C_q = 0.072$ ($h/H = 0.4$), the vortex was generated not as a result of loss of stability of one of the shear layers, but after the merging of these layers. For the values of the flow-rate coefficient $C_q = 0.13$, 0.142 a small-scale vortex structure was formed behind models 4 and 7, respectively, which is typical of a jet flow.

Discussion of the Results. A comparison of the turbulence characteristics of the flow behind models with a slot of different width in the base with similar characteristics obtained for an emerging jet revealed a number of common features. The mean-velocity defect increased and the width of the wake decreased with increase in the size of the slot and the flow rate of the emerging jet. The degeneration of the defect ΔU was described by power laws with different exponents: $n = -0.5$ (behind models 6–8), $n = -0.4$ (behind models 1–4 [9]), $n = -0.2$ (behind models 6–8 in the absence of ejection). It is logical to assume a dependence between the exponent n and the magnitude of the flow rate of the emerging jet. In this case the increase in the velocity defect observed behind models with sufficiently wide slots $h/H > 0.1$ can be explained by the same physical cause, i.e., emergence of the medium induced by nonstationary separation of shear layers from the aft edge of the model. This assumption confirms the analysis of the distributions of the velocity fluctuations. They decreased when a jet was ejected, but the narrower the slot, the less they differed from similar fluctuations behind the base model [9]. The fluctuations behind models with slots $h/H < 0.75$ with no emergence of a medium increased, but for $h/H > 0.75$ they decreased, compared to the fluctuations behind the base model.

Thus, an increase in the size of the slot in the aft edge of the model or in the flow rate of the emerging jet is accompanied by a similar transformation of the turbulence characteristics of the flow behind the body, i.e., the "cavity effect" is explained by periodic ejection of the medium through the slot due to a nonstationary flow behind the body. It must especially be emphasized that the internal cavity of the model was reliably insulated from the supplying air conduits in investigation of the effect of the slot width. The emergence of a jet from a slot was caused by periodic separation of shear layers from the opposite edges of the model base. Nonstationarity is a necessary condition for manifestation of the "cavity effect." Investigations [10] showed that at a Mach number $M = 1$, when there was a stationary flow behind the body, the bottom pressure for the base model and a model with a cavity was the same. The mean-velocity profile behind a model is formed as a result of the interaction of a vortex structure with a potential flow. The more intense the vortex, the more rapid the leveling out of the velocity field downstream, i.e., the smaller the magnitude and the higher the rate of degeneration of the defect ΔU. Induced emergence of a medium through a slot probably decreases the intensity of the vortex formed and, as a result, the agitation of the flow behind the model. This results in an increase in the mean-velocity defect and a slowing down of the rate of its degeneration (see Fig. 3). Ejection of a medium from a slot led to an earlier interaction of the shear layers, which was responsible for the increase in the level of the fluctuations in comparison with similar fluctuations behind the base model. As the width of the slot increased, the interaction of these layers became more difficult. An increase in the volume of the ejected medium entrained in the shear layers was accompanied by a decrease in the initial concentration of the vorticity of the layers and led to a decrease in the level of the fluctuations of the vortex being formed [11].

A decrease in the intensity of the vortex wake under the effect of an ejected jet was noted in [12]. The increase in the frequency of the shedding of shear layers from the edges of the model base [5] and in the mean-velocity defect on the wake axis and the decrease in the level of the longitudinal and transverse fluctuations and in the width of the wake that were established by the present investigations indicate, besides this, also a decrease in the scale of the vortex being formed behind the body. The smaller the scale and intensity of the vortex, the more rapidly it degenerates and the flow structure passes over to a state that no longer depends on the initial conditions. This region of the wake is known as the region of a self-similar flow, in which the changes in the turbulence parameters are described by the power laws ΔU, u_1, $u_2 \sim (x)^{-0.5}$; δ_U, δ_1, $\delta_2 \sim (x)^{0.5}$. As is seen (Fig. 5), under the influence of a jet emerging through a slot with $h/H \geq 0.1$, the noted characteristics, except for the transverse fluctuations, were described by self-similar power laws beginning from the distance $x/H = 15$. However, the degeneration of the transverse fluctuations was slowed down considerably, and their values decreased and approached those for the longitudinal fluctuations. The decrease in the anisotropy of the wake flow also points to a decrease in the scale of the vortices behind the body.

A comparison of the distributions of the turbulence characteristics (see Figs. 2 and 4) with the picture of the structure of the flow behind the models (Fig. 6) showed that the compared parameters in fixed cross sections with a jet emerging through narrow and wide slots relate to different stages of flow development. In the cross section with $x/H = 3$ behind models 7 and 8 the measurements were made before formation of a vortex, and behind models 1–4, after formation of one. This explains the substantially lower values of the longitudinal and transverse fluctuations behind models 7 and 8. Shear layers merged at a distance $x/H = 7$ from the base of model 8 and caused growth of the longitudinal and transverse fluctuations by 11 and 42%, respectively. The profiles of the fluctuations behind models 4 and 7, 8, that are associated with the position of the first pair of vortices in the wake are at $x/H = 3$ and $x/H = 7$, 10. An analysis of these distributions showed that the wider the emerging jet (the greater the flow rate of the jet), the lower the level of the fluctuations generated by the vortex formed and the narrower the wake. A comparison of the profiles of u_1 and u_2 behind models 4 and 7 in the cross sections before formation of a vortex (the cross sections $x/H = 1$ and 3, respectively) gives information about the level of the fluctuations in the shear layers and in the region of emergence of the jet. The maximum values, which characterize the state of the shear layers, behind model 4 exceeded those behind model 7 by 20% for the longitudinal and 33% for the transverse fluctuations. Thus, one can see a direct relationship between the volume of the ejected medium entrained in the shear layers, the decrease in the level of the fluctuations of these layers, and, as a consequence, the decrease in the level of the fluctuations generated by the vortex formed. The results confirm a qualitative evaluation of the decrease in the degree of circulation $\partial\Gamma/\partial t$ in a wake under the influence of an ejected jet [12]. Since $\partial\Gamma/\partial t = f(\varepsilon)$, where ε is the vorticity of the shear layers, the decrease in the circulation points to a decrease in the primary vorticity upon entrainment of the medium ejected, which carries a vorticity of the opposite sign.

Conclusions. The investigations carried out show that under the action of ejection the conditions of formation of a vortex wake change. The size of the vortex formed behind a model and its intensity decrease. This is accompanied by an increase in the velocity defect and a decrease in the level of the fluctuations. The volume of the medium entrained in the shear layers and leading to a decrease in their primary concentration of vorticity exerted a determining influence on the formation of a vortex and the characteristics of the wake-flow turbulence. The lower this level, the farther from the base of the model was the vortex formed and the lower its intensity and size.

The "cavity effect" on the base of the model, responsible for the change in the bottom pressure, arises under the influence of periodic separation of shear layers from the surface of the model that induce emergence of the medium from the cavity.

NOTATION

V_j, velocity of the ejected jet at the cut of the slot, m/sec; U_∞, velocity of the potential flow, m/sec; U_i, instantaneous value of the mean velocity in the cross section of the wake, m/sec; $\Delta U = U_\infty - U_i$, mean-velocity defect, m/sec; u_1, longitudinal velocity fluctuations, m/sec; u_2, transverse velocity fluctuations, m/sec; δ_U, half-width of the wake determined from the mean-velocity profile, m; δ_1, δ_2, half-width of the wake determined from the profile of the longitudinal and transverse fluctuations, respectively, m; H, height of the model base, m; Γ, circulation; h, width of the slot, m; x, coordinate in the direction of the flow, m; $C_q = hV_j/HU_\infty$, coefficient of ejection; $\mathrm{Re} = HU_\infty/\nu$; $\mathrm{M} = U_\infty/a$; a, speed of sound in air, m/sec; ν, kinematic viscosity, $\mathrm{m}^2/\mathrm{sec}$. Subscripts: ∞, potential flow; *j*, ejected jet; *i*, instantaneous coordinate; 1, longitudinal velocity fluctuations; 2, transverse velocity fluctuations; *U*, mean flow velocity.

REFERENCES

1. A. Roshko, On the Drag and Shedding Frequency of Two-Dimensional Bluff Bodies, NASA TN N 3169 (1954).
2. C. J. Wood, J. Roy. Aero. Soc., 68, 477-482 (1964).
3. P. W. Berman, Investigation into Effect of Base Bleed on the Flow Behind a Two-Dimensional Model with a Blunt Trailing Edge/AGAR-CP-4, Pt. 2 (1966), pp. 485-507.
4. C. J. Wood, J. Fluid Mech., 29, 259-272 (1967).
5. V. L. Zhdanov, Inzh.-Fiz. Zh., 71, No. 4, 632-638 (1998).
6. J. M. Cimbala and W. J. Park, J. Fluid. Mech., 213, 479-509 (1990).
7. Tamoutsu Igarashi, Bull. JSME, 21, No. 154, 656-664 (1978).
8. V. L. Zhdanov and G. Ékelmann, Inzh.-Fiz. Zh., 66, No. 3, 259-262 (1994).
9. V. L. Zhdanov and G. Ékelmann, Experimental Investigation of the Change in the Structure of a Flow behind a Two-Dimensional Body under the Influence of an Ejected Jet, Preprint No. 11 of the Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of the BSSR," Minsk (1991).
10. J. F. Nash, V. G. Quincey, and J. Callianan, Experiments on two-dimensional base flow at subsonic and transonic speeds, NPL AERO Report 1070 (1963).
11. J. H. Gerrard, J. Fluid Mech., 25, 401-414 (1966).
12. C. J. Wood, J. Fluid Mech., 29, 259-272 (1967).