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EFFECT OF THE CONFIGURATION OF A DISCHARGED JET ON THE CHANGE IN THE BASE PRESSURE OF A MODEL AND THE STROUHAL NUMBER IN THE WAKE

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The article presents results of an experimental investigation of the change in the base pressure of a two-dimensional model and the shedding frequency of shear layers under the action of two jets that are bled out of slots made along the upper and lower edges of the base of the model.

Introduction. The value of the pressure on the base of a model is determined by the structure of the vortex wake behind the model. This structure is formed by the boundary layers shed from the rear edge of the base. Measurement of the pressure distribution behind the model showed that the minimum value was exhibited at a certain distance downstream that corresponded to the coordinate of the first vortex [1]. The rarefaction on the rear edge of the body is greater, the higher the intensity and scale of the vortex formed by shear layers. The jet bled out of a slot made along the horizontal axis of symmetry of the base of the model was responsible for growth of the base pressure and the shedding frequency of shear layers [2-4]. The intensity of the formed vortex decreased, as evidenced by the decrease in the level of pulsations and the width of the wake flow [5]. These data correlate with the decrease in the circulation of a vortex as a result of bleed-out of the medium [2]. The circulation around a closed path along the main flow is

$$\Gamma = \int \text{rot } \mathbf{v} \, ds ,$$

where ds is a surface element that rests on the loop. The vector rot v is called the vorticity (ε) of the flow at the given point. For a two-dimensional flow rot v = $(\partial u/\partial y - \partial v/\partial x)$, and in the boundary layer it is equal to

$$\text{rot } \mathbf{v} = \partial u/\partial y .$$

The flow of vorticity through the cross section of a boundary layer of unit thickness is equal to $u\varepsilon dy$, and the total flow of vorticity transferred by the boundary layer directly before shedding from the rear edge of the two-dimensional model is

$$Q_\varepsilon = \int_1^2 u \, (\partial u/\partial y) \, dy = (U_e^2 - U_i^2)/2 ,$$

where U_e and U_i are the velocities on the external and internal boundaries of the shear layer ($U_i = 0$ in ordinary cases). The intensity of a vortex street is determined by the vorticity entering the vortex prior to its separation from the feeding shear layer. Thus, the vorticity flow of the shear layer decreases if in front of the edge of separation there is a jet that escapes from the base of the model with the velocity V_j.

The entrainment of the medium into shear layers, for example, that blown through a slot, changes the initial vorticity of the layers and the conditions of the formation of a vortex. The discharged jet has a vorticity of opposite sign, and therefore the larger the volume of the medium entrained, the smaller the vorticity flow of the

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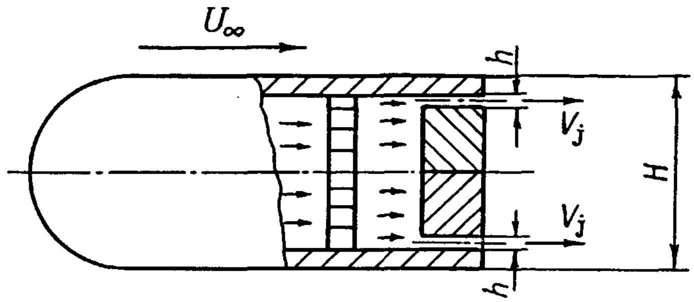

Fig. 1. Schematic of the model.

layers; this is accompanied by a drop in the level of turbulent pulsations in the wake [5]. The scheme described is valid when there is a common boundary of interaction between the shear layer and the discharged medium, i.e., when the width of the slot is comparable to the thickness of the rear edge of the model. When the medium escapes through a narrow slot, the interaction becomes more complex due to the appearance, between the shear layers and the jet, of a weakly turbulent region on whose boundary the two flows generate vortices of small scale but opposite vorticity [6]. Investigations showed that the intensity of the vortex formed behind the model changed less, the narrower the slot, despite the larger velocity of jet bleed ($V_j = 1.4U_\infty$) [5]. Correspondingly, the base pressure increased to a lesser extent, but the shedding frequency of shear layers increased substantially. The zone of formation of the vortex behind the body is determined by the relationship between the volume of the medium entrained into shear layers and the induced backward flow along the axis of the wake. Jet bleed through a slot made along the horizontal axis of symmetry of the base of a model exerts an effect both on the shear layers (entrainment of this medium into the layers) and directly on the recirculation flow, suppressing its propagation toward the base of the model. It is of interest to determine to what extent the bottom pressure and the shedding frequency of shear layers change if the discharged medium acts mainly on the shear layers and does not exert a direct effect on the induced backward flow. This case is realized when there is symmetric escape of two narrow jets near opposite edges of the base of the model.

Experiment. The investigations were carried out in an open-type wind tunnel [4] at a flow velocity of 14 m/sec in the working part of the channel. The model was a two-dimensional body with semicircular leading and blunt trailing edges [4]. The base of the model was formed by two rectangular blocks mounted so that a slot of width $h/H = 0.05$ was formed between the upper and lower plates of the model and each of the blocks (Fig. 1). A system of holes in the central vertical plane of each block provided measurement of the averaged pressure over the base of the model [4]. The magnitude of the pressure was characterized by the pressure coefficient $(C_p)_b$. Air was delivered into the model symmetrically from two sides, and its flow rate was controlled in each channel. A honeycomb was installed inside the model to ensure homogeneity of the discharged medium. The bleed coefficient C_q was determined as the ratio of the total flow rate of the discharged medium to the flow rate of the potential flow through the cross section of the model.

The shedding frequency of shear layers (the frequency of vortex formation) was established by means of a single-filament gauge behind the body in the potential flow at a distance of two diameters downstream. The output signal of the gauge entered a Dantec anemometer and then a Nicolet 660 spectral analyzer.

Results of Investigations and Discussion. The dependence of the pressure coefficient on the bleed coefficient is characterized by the presence of two practically identical maxima: $(C_p)_b = -0.49$ at $C_q = 0.037$ and $(C_p)_b = -0.5$ at $C_q = 0.11$ (Fig. 2). The first maximum of the base pressure was recorded at a velocity of the jet discharge from the slot equal to $V_j = 0.4U_\infty$, and the second at $V_j \approx U_\infty$. A comparison with a similar dependence obtained for a jet discharged from a slot of width $h/H = 0.05$ and 0.1 made along the axis of symmetry in the base of the model [4] showed that not only the values of the base pressure and the shedding frequency of shear layers, but also the behavior of these parameters differed.

The dependence of the Strouhal number was characterized by a slightly rising, almost horizontal segment in the range of change of the bleed coefficient $0 < C_q \leq 0.1$. A rapid increase in the frequency similar to that observed in bleed of a central jet through a narrow slot [4] was observed for $C_q \geq 0.11$ (Fig. 2).

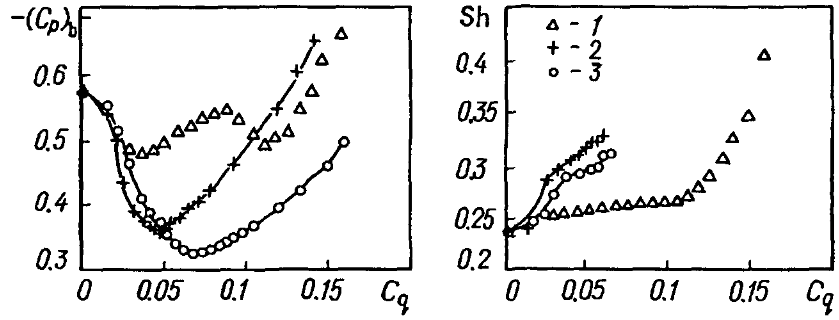

Fig. 2. Dependence of the pressure coefficient and the Strouhal number on the change in the bleed coefficient of the jet: 1) two symmetric slots, $h/H = 0.05$, 2) central slot, $h/H = 0.05$, 3) the same, $h/H = 0.1$.

For $C_q \leq 0.02$ the discharge of the medium through two slots located near the upper and lower edges of the base of the model was responsible for the more rapid increase in the base pressure compared with bleed of a jet through a central slot with the same dimensions (Fig. 2). This can indicate effective entrainment of two jets in shear layers, which leads to a decrease in the flow of vorticity of the layers and formation of a weaker vortex. The virtually identical change in the Strouhal number in discharge of symmetric and central jets ($C_q \leq 0.02$) indicates that the dominant factor that influences the rise in the base pressure is entrainment of the discharged medium in shear layers. At low flow rates the size of the vortex and the extent of the zone of its formation are independent of the configuration of the jets. An increase in the flow-rate coefficient ($C_q \leq 0.035$) is accompanied by a weak change in the Sh number and the base pressure, while for a central jet a typical feature is a rapid increase in both parameters due to a decrease in the scale of the vortex and its intensity [4, 5]. The first maximum of the base pressure for the configuration of two jets was observed at virtually the same flow rates as the maximum of the pressure during the discharge of a central jet through a slot with $h/H = 0.05$ (Fig. 2). It is evident that the velocities at the cut of the slots were related as one to two. An increase in the width of the central jet to $h/H = 0.1$ displaced the maximum of the base pressure toward higher values of C_q. We note that the velocity of the discharge of the central jet is the same as for the two symmetric jets, $V_j \sim 0.8U_\infty$. The increase in the rarefaction on the bottom of the model observed for the configurations considered is associated with the ejection properties of jets. The central jet, which entrains the environment, caused approach of the shear layers and earlier interaction of them, leading to an increase in the Strouhal number. The symmetric jets stabilized and ejected the medium from the central region of the weakly turbulent flow adjacent to the base of the model, i.e., the extent of the zone of formation of the vortex virtually did not change, as evidenced by the small change in the Strouhal number up to values $C_q \leq 0.11$.

As the flow rate of the jets increases, one must also expect elongation of the shear layers, i.e., movement of the coordinate of the first vortex away from the model. As is known, this process is accompanied by an increase in the base pressure. Thus, on the one hand, due to an increase in the entrainment of the medium adjacent to the base of the model, the jets promote a decrease in the base pressure, and, on the other hand, by causing elongation of the shear layers and removal of the formed vortex from the model, they lead to growth of the base pressure. In the range of flow rates $0.04 \leq C_q \leq 0.08$, the ejection action of the jets dominates, thus explaining the decrease in the base pressure. When $0.08 \leq C_q \leq 0.11$, the effect of removal of the vortex from the base of the model dominates. The second maximum of the pressure, recorded at $C_q = 0.11$, seems to be due to this. At velocities $V_j \geq U_\infty$ ($C_q \geq 0.11$) the base pressure is determined entirely by the ejection effect of the two jets. The displacement of the peak of the dominating frequency in the spectrum of velocity pulsations toward higher values for $0.11 \leq C_q \leq 0.16$ testifies to formation of a vortical structure of decreasing scale behind the model. When a jet was ejected through a central slot of equivalent width, the flow regime behind the model passed from the wake mode to the jet mode, which is characterized by a uniform distribution of pulsations over frequencies, for $C_q \geq 0.06$ (Fig. 2).

Conclusions. The investigations showed that jet bleed through slots located near the points of shedding of shear layers was responsible for the prevailing growth of the base pressure in comparison with jet bleed through a central slot of the same size, but only at low values of the flow rate, namely, $C_q \leq 0.02$. As the bleed coefficient increased, the dual character of the effect of symmetric jets on the value of the base pressure was manifested: the base pressure decreased due to the ejection effect, but it increased due to the elongation of the shear layers and the formation of a vortex at a large distance from the base of the model. As a consequence, the resultant value of the coefficient $(C_p)_b$ was smaller than that established under the influence of a central jet. The discharge of two jets stabilized the vortical structure of the wake in a wide range of flow rates $0.02 \leq C_q \leq 0.1$, as reflected by the weak change of the dependence of the Strouhal number on the flow rate.

NOTATION

H, height of the base of the model, m; h, width of a slot, m; $C_q = hV_j/HU_\infty$, bleed coefficient; V_j, jet velocity at the cut of the slot, m/sec; U_∞, velocity of potential flow, m/sec; v, vector of the instantaneous velocity, m/sec; u, instantaneous value of the longitudinal component of the velocity, m/sec; v, instantaneous value of the transverse velocity component, m/sec; $(C_p)_b = (p_b - p_\infty)/0.5\rho U^2$, pressure coefficient; p_∞, static pressure in potential flow, Pa; p_b, static pressure on the base of the model, Pa; $\mathrm{Sh} = fH/U_\infty$, Strouhal number; f, shedding frequency of shear layers, Hz; $\mathrm{Re}_H = HU_\infty/\nu$, Reynolds number; ν, kinematic viscosity, m^2/sec; ρ, air density, kg/m^3; x, coordinate along the flow, m; y, coordinate in the direction normal to the flow, m. Subscripts: ∞, potential flow; j, discharged jet; b, parameters measured on the base of the model; e, i, external and internal boundaries of the boundary layer.

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