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SELF-EXCITATION OF VORTEX STREET INTENSITY BEHIND A PLANE MODEL WITH A BODY IN ITS WAKE

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The study discovered critical conditions under which there is a periodic increase in the Karman vortex street intensity and an increase in pressure pulsations with a change in the distance between a plane model and a body in its wake.

The effect of various external forces on the process of vortex formation behind a model was investigated in [1-3]. The interest in such studies stems from the need to suppress vortex formation in order to reduce the drag of poorly-streamlined bodies.

Similar investigations of the effect of splitter plates on vortex formation in the wake of a plane model were conducted in [4]. The dimensionless frequency of convergence of the vortex without the plate was Sh = 0.24. With an increase in the length of the plate, the dimensionless frequency increased until the ratio of the plate length to half the thickness of the trailing edge $\bar{l} = 1.5$. Here, the value of Sh began to drop sharply; no vortex formation was observed at $\bar{l} = 2.5$, and the pressure coefficient increased. The effect of a splitter plate affixed behind a cylinder along the wake axis on the frequency characteristics of the wake and the resistance coefficient was studied in [2]. It was observed experimentally that the location of a splitter plate behind the cylinder on the wake axis stops vortex formation and lowers the resistance of the cylinder by about 50%. It was shown that the base pressure increases when the plate is moved away from the cylinder to a distance equal to about four cylinder diameters, and that this is accompanied by a reduction in vortex convergence frequency. Any large displacement of the plate is accompanied by a sharp increase in the vortex convergence frequency, to nearly its initial value, and a corresponding sharp decrease in base pressure.

It was shown in [5, 6] that the formation and separation of discrete vortices behind a plane model are accompanied by pressure pulsations near the trailing edge and the propagation of density waves in the flow at a frequency equal to the vortex convergence frequency. In [7] a study was made of the wave intensity and length, the directionality of the vortex sound, and the propagation of sound waves radiated by the vortex street. Also examined was the nature of interaction of the pressure pulsations in the flow and the sound waves radiated by a Karman street. Pressure pulsations and sound waves generated by mediums which are similar in spectral composition but physically quite different may interact, changing the pressure in the region of vortex formation and the intensity of the Karman vortex street.

In the present work, we studied the features of vortex formation with a change in pressure in the region of vortex formation behind a plane model with a body located in its wake. We also studied the effect of pressure pulsations in the wake on the intensity of the vortex formation process.

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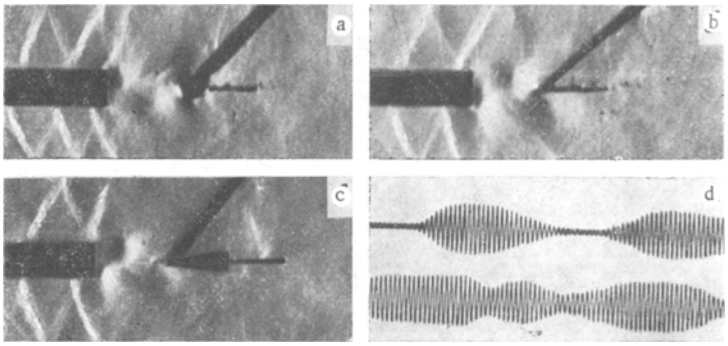

Fig. 1. Photographs of vortex wake and density waves in flow about a plane model with a body in its wake ($M_1 = 0.9$): a) cylinder; b) plate; c) wedge in the wake of the model; d) oscillogram of pulsations of density gradients in the model wake.

The formation of an unsteady flow behind a body was examined using the example of flow about a plane model of length $L = 180$ mm with a straight trailing edge $H = 10$ mm. Located in the wake behind the model at different distances from the trailing edge were a cylinder of 10 mm diam., a wedge of length $l = 20$ mm with a base $h_1 = 6$ mm, and a plate 18 mm long and 1.5 mm thick. The basic geometric parameters of the investigated models were varied within the following ranges: $d/H = 1$; 0.6; 0.15; $x/H = 0$–6, where d is the midsection of the body and x, the distance between the model and the body. All of the bodies studied had a tail fin 15 mm long. The fin prevented the formation of a vortex street behind the bodies and, thus, interaction of such a street with the object of our study – the vortex wake of the plane model [2].

The experiments were conducted in a closed-type steam wind tunnel with the range of numbers $M_\infty = 0.4$–0.7 ($M_1 = 0.6$–0.9 in the working-channel cross section corresponding to the trailing edge of the model) and $Re = (1.75\text{–}2.1) \cdot 10^6$, with the model length L having been chosen as the base geometric parameter. The working channel of the unit had a rectangular cross section 100×60 mm. Perforated plates installed on the floor and roof of the channel formed a plane, gradient-free nozzle with a cross section 70×60 mm. The inlet section of the nozzle was shaped according to the Vytoshinsky formula. The permeability coefficient of the plates was $s = 0.26$. The side walls of the working channel had a window 165 mm in diameter where the model was located to permit installation of grade K-108 optical glass, which made it possible to directly observe the processes being studied and to use optical measurement methods. An IAB-451 shadowgraph was used to aid in the measurements. Special traversing equipment was installed on the roof of the working channel to make it possible to traverse the flow with probes to determine static pressure and stagnation pressure in the wake, as well as to move the bodies located in the model wake.

The amplitude and frequency of the pulsations in base pressure were measured with a piezoceramic pressure transducer based on TsTS-21 ceramics. The natural frequency of the transducer $F_p = 70{,}000$ Hz at a receiving-membrane diameter of 5 mm and thickness of 20 mm. The frequency characteristic was linear up to the frequency at which the investigated signal was recorded $F \le 0.2F_p$. The sensitivity with the action of the pressure pulse over the entire surface of the receiving membrane $\gamma = 0.209$ mVA/mm H_2O at a cable capacitance of 290 pF. The frequency of the base-pressure pulsations and the density waves propagating in the flow was measured with an S5-3 low-frequency analyzer.

To record the process frequencies, the electric signal from the piezoceramic pressure transducer was sent to the input of a U2-6 measuring amplifier operating in the "1st narrow" selective mode in the frequency range 20–30,000 Hz, with a wide band at the level corresponding to 0.76–10% of the selection frequency for any frequency within the range investigated.

The output signal of the U2-6 amplifier was recorded on a cathode-ray oscillograph with an NO-23 mechanical scanner, designed to record the light beam on the cathode-ray tube on film with a sensitivity of 600–1000 unit fast-alternating electrical oscillations within the frequency range from 0 to 50,000 Hz. The amplitude of the base-pressure pulsations was measured by comparison of the investigated signal with a calibration voltage. For this purpose, the signal from the piezoceramic pressure transducer was sent directly to one of the inputs of an S1-18 dual-trace oscillograph.

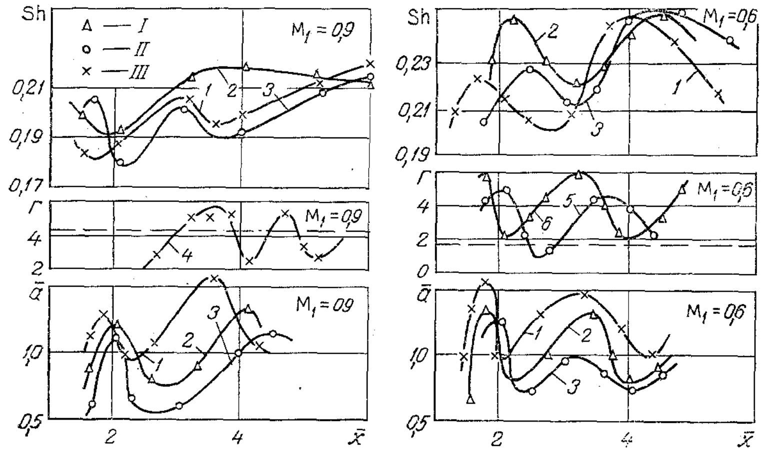

Fig. 2. Change in relative intensity of vortices $\bar{a}$ in the Karman street: 1) wedge; 2) plate; 3) cylinder in the model wake. Circulation of Karman vortex wake Γ: 4) wedge; 5) cylinder; 6) plate in the model wake. Dimensionless frequency of vortex convergence: 1) wedge; 2) plate; 3) cylinder in the model wake. I) $\bar{h}$ = 0.15; II) $\bar{d}$ = 1; III) wedge.

The frequency of the density-gradient pulsations in the wake was measured with a photoelectronic apparatus positioned in the focal plane of the IAB-451 shadowgraph. The FÉU-51 photomultiplier, with a receiving-diaphragm diameter of 1.5 mm, was installed on the micrometric traversing equipment, making it possible to record the form and frequency of the density-gradient change in different regions of the wake and in the zone of density wave propagation. As noted above, an S5-3 low-frequency analyzer was used to analyze the spectral characteristics of the investigated signal.

The experimental data, obtained in the form of oscillograms of local density gradients in the vortex wake over time, were analyzed statistically on a "Minsk-22" computer. Since the flow in the wake was of an intermittent character and the regular vortex street was replaced for different time intervals by full turbulent mixing, it was necessary to evaluate the duration of the continuous streets and the intensity of the vortices with changes in the flow conditions and the geometry of the bodies placed in the wake of the model.

To determine the duration of the continuous vortex street, we obtained the envelope of the high-frequency component of the oscillogram which corresponded in frequency to the vortex convergence frequency (Fig. 1d). The envelope of the oscillogram amplitudes was the low-frequency component, the frequency of which characterized the change in the structures of the vortex wake. Here, the amplitude qualitatively characterizes the change in the intensity of the vortices and is equal to the amplitude of the high-frequency component. To evaluate the relative change in vortex intensity, the amplitude of the oscillogram of density gradients in the model wake was referred to the amplitude of the unperturbed wake (no body behind the model). The absolute values of vortex intensity on a regular section of the wake were determined from the Karman formula $\Gamma = 2bc_V/\text{th}\, \pi h/b$ using photographs of the vortex street (Fig. 1).

Figure 2 shows the change in the amplitude of the oscillogram of density gradients in the wake $\bar{a}$, referred to the amplitude of the unperturbed wake, in relation to the relative distance $\bar{x} = x/H$. With a change in the distance $\bar{x}$ between the model and the body, there is a periodic change in the intensity of the vortex street. The figure also shows the change in the circulation of the vortices Γ, determined with the Karman formula using photographs of the vortex street. The dashed line represents the circulation of vortices in an unperturbed wake behind the model.

There are practically no studies of the duration of a continuous vortex street behind a poorly-streamlined body. The literature contains only isolated data characterizing the intermittence factor of the vortex street behind a model. For example, an intermittence factor $\gamma = 0.02$ is cited in [6] for flow about a wedge at M = 0.4.

To determine the frequency of the change in the structures of the vortex street, we studied the energy spectra of the oscillogram envelope (Fig. 1d) for different distances between the model and body. The spectra show narrow-band components of appreciable intensity, making it possible to distinguish the characteristic frequency of the change in vortex street structures for each distance x between the model and body. The frequency values were replaced by values of the duration of the continuous vortex street $T = 1/f$.

Study of the oscillogram energy spectra allowed us to determine the characteristic duration of the continuous vortex street in relation to the distance between the model and body. As a dimensionless characteristic of the duration of the street, we took the duration coefficient $\gamma = T/\Sigma T$, which characterizes the ratio of the time T of the continuous vortex street corresponding to the narrow peak on the energy spectrum to the total recording time. It was found that at distances between the model and body corresponding to the maximum vortex intensity, the street becomes nearly continuous; at the distance corresponding to the minimum, the absolute duration of the continuous vortex street decreases to $1 \cdot 10^{-3}$ sec and the duration coefficient acquires a value of 0.07.

The body placed in the wake has a substantial effect on the vortex convergence frequency, the latter decreasing sharply as the vortex intensity increases. The Strouhal number $Sh = nH/c$, corresponding to the measured vortex convergence frequency n, is shown in Fig. 2. Similar effects were noted throughout the investigated range of conditions ($M_1 = 0.6$-0.9).

The completed analysis of vortex street characteristics permits us to make the following conclusions:

a) a body moving in the wake near a plane model causes an abrupt periodic change in the intensity of the vortices, the frequency of convergence of some, and the duration of the continuous vortex street;

b) the highest-intensity vortex wake is produced by a body with a small leading edge (wedge and plate) located in the wake of the model.

The study of the characteristics of the wake showed that there is a significant negative pressure close the trailing edge of the body, in the region of formation of discrete vortices [2]. The static pressure along the central axis of the wake quickly decreases, reaching a minimum value at a distance equal roughly to half the thickness of the trailing edge of the body. It then returns to a certain value below the static pressure in the external flow. The phenomenon of suppression of vortex formation in the case of location of a splitter plate behind the cylinder on the wake axis is explained in [2] by the fact that the plate eliminates the low-pressure region on the wake axis, and the dynamics of vortex formation is connected with the existence of this region. In [8], a direct connection was also found between the intensity of the vortices and the magnitude of the local negative pressure close to the trailing edge of the body. The author here also proposed the existence of a reciprocal relationship, whereby the intensity of vortex formation could be affected by changing the pressure distribution in the vortex-formation region.

The study of a body placed in the wake of a model also showed that the body changes the pressure distribution in this region, increasing the static pressure in the depression to the value of the stagnation pressure at the forward stagnation point of the body.

The greatest deformation of the static-pressure depression is caused by the plate placed in the model wake. The plate significantly increases the pressure downstream from the depression, effecting almost no change in the base pressure of the model compared to the unperturbed wake. An increase in the body cross section (cylinder) is accompanied by an increase in pressure in the vortex depression and in the base pressure of the model.

Thus, the depth of the vortex depression is greater in the case of the plate, and the mean intensity of the vortex street is higher as well.

Together with effecting a change in the mean pressure in the vortex depression, a body placed in the wake affects the pulsational characteristics of the pressure in the region of vortex formation. Two sources of pressure pulsation were observed experimentally in the vortex wake behind the model: in the region of vortex formation close to the edge of the model, and at the forward stagnation point of the body placed in the model wake.

On the basis of our physical model of the phenomena of a periodic change in vortex wake parameters with a change in the distance between the model and the body, we made an assumption regarding the connection between the intensity of the vortex formed close to the edge of the model and the instantaneous distribution of static pressure in the vortex depression. The formation and separation of the vortices is due to pressure fluctuations in the vortex depression and fluctuations of the base pressure of the model.

Figure 3 shows the change in the relative amplitude of the pulsations in base pressure A.

A body with a relatively small leading edge causes a maximum increase in the amplitude of the base-pressure pulsations, the highest-intensity vortices (Fig. 2), and sharp deformation of the static-pressure depression behind the model.

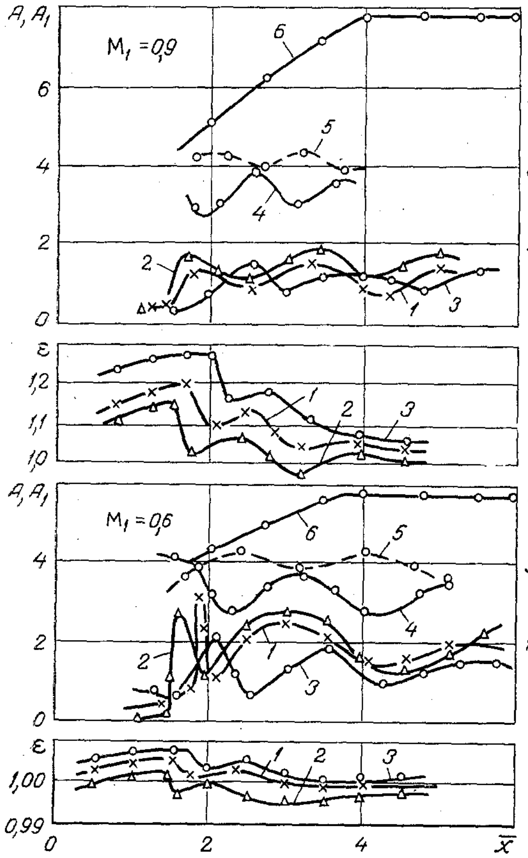

Fig. 3

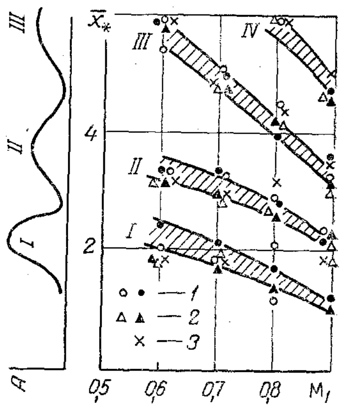

Fig. 4

Fig. 3. Dependence of base pressure ε on distance between model and body; amplitude of pulsations of base pressure A: 1) wedge; 2) plate; 3) cylinder in the model wake; 4) change in intensity B of doubled and 5) basic frequencies of model base-pressure pulsations with a cylinder located in the model wake; 6) amplitude of pressure pulsations at the forward point of the cylinder.

Fig. 4. Critical distance $\bar{x}_*$ between model and body corresponding to resonance effects I-IV: 1) cylinder, $\bar{d} = 1$; 2) plate, $\bar{h} = 0.15$; 3) wedge in the model wake. The dark points denote calculated values, and the clear points denote experimental values.

The frequency of the base-pressure pulsations as measured by the piezoceramic pressure transducer proved to be the same as the frequency of the density-gradient pulsations in the vortex street, measured with the photoelectronic apparatus. Together with the basic "Karman" frequency – characterizing the change in the center of application of the load to the model – we recorded the periodic fluctuations at the doubled frequency, corresponding to the process of fluctuation of the pressure in the vortex depression with the formation and separation of each vortex. Figure 3 also shows the change in the intensity B of the basic and doubled frequencies, expressed in decibels, for the case of a cylinder located in the model wake at different distances $\bar{x}$. The intensity of the doubled frequencies is considerably lower than the intensity of the basic frequencies throughout the entire range of distances, except for the critical values $\bar{x}_*$. At the critical values, there is an increase in the amplitude of the base-pressure pulsations and the circulation of the vortices. In this case, the intensity of the doubled frequencies increases to the level of the basic frequencies.

The pressure pulsations close to the trailing edge of the model are accompanied by the propagation of density waves in the flow, at a frequency equal to the vortex convergence frequency, and by vortex sound. Shadowgrams obtained with the IAB-451 recorded density waves propagating counter to the flow along the top and bottom surfaces of the model and shifted by half a period. Density waves and low-pressure waves propagating along the flow were detected with the piezoceramic pressure transducer positioned behind the model outside the vortex-formation region 30 mm below the central axis of the wake. The amplitude and frequency of the density waves recorded by the transducer in this position were $A = 7.35 \cdot 10^{-2}$ MPa and $n = 7200$ 1/sec at $M_1 = 0.6$. Under the same conditions in the unperturbed wake, $A = 8.35 \cdot 10^{-2}$ MPa, $n = 7200$ 1/sec. The length of the density wave propagating in the direction of the flow was 4-10 times as great as the length of the waves moving counter to the flow which were recorded by the IAB-451 (Fig. 1).

The base pressure is an important hydrodynamic characteristic of flow about the model, and the possibility of increasing this pressure with the aid of a body placed behind the model was investigated in greater detail. Figure 3 shows the change in the relative base pressure of the model $\varepsilon = p_b/p_{b0}$ in relation to the distance of the model from the body. A change in this distance is accompanied by a periodic change in the base pressure, with a reduction in pressure being associated with a sharp increase in the amplitude of the pulsations.

The body located in the model wake is a secondary source of pressure pulsations. The piezoceramic pressure transducer, placed at the forward end of the cylinder, detected the existence of a pulsating source of pressure at the cylinder's forward stagnation point.

Visualization of the vortex wake shows that, throughout the range of conditions investigated, the vortex street disintegrates when it encounters a body behind the model, and practically no sign of the street is detected behind the body (Fig. 1). Disintegration of the vortex street causes a periodic change in pressure at the end of the body from roughly the stagnation pressure to the negative pressure in the vortex.

The pressure pulsations measured at the end of the cylinder proved to be quite large. They were 4-7 times greater than the pressure pulsations about the cylinder when it was removed beyond the model wake. Curve 6 in Fig. 3 shows the change in the relative amplitude of the pulsations $A_1 = \sqrt{\overline{p_0^2}}/\sqrt{\overline{p_{00}^2}}$ with different distances between the model and cylinder.

The frequency of the pressure pulsations at the forward point of the body corresponds to the doubled pulsation frequency (2n). We also recorded the basic "Karman" frequency, the intensity of which (expressed in decibels) was substantially lower than the intensity of the doubled pressure-pulsation frequency.

Control of the intensity of vortex formation is connected with changing the pressure in the vortex depression, located at a distance from the edge of the model equal to roughly one gauge. The two centers of perturbation in the wake behind the model – the intensive center at the forward point of the body and the weaker center on the edge of the model – interact with one another. The periodic pressure fluctuations in the vortex depression with the formation and separation of vortices create a system of density and low-pressure waves which propagate in the surrounding flow with a frequency of 2n. When the vortex street interacts with a body located in the wake of the model, periodic pressure fluctuations are seen at the forward stagnation point of the body. These fluctuations serve as the center of density-wave propagation, the density waves having a preferred frequency of 2n. A change in the distance between the model and the body may result in a resonance superposition of density and low-pressure waves on the fluctuations in the static-pressure depression behind the model. This in turn will lead to deepening of the vortex depression or, if the appropriate superposition of density waves occurs, to a reduction in the depression and thus an increase or decrease in the intensity of vortex formation. The intensity of the doubled frequencies 2n increases in this case. The density waves play the role of feedback in the vortex-wake–body system.

The change in pressure in the vortex depression will be greatest if the antinode of the secondary wave propagating from the body coincides with the antinode of the primary wave from the static-pressure depression. The change in pressure in the vortex depression will be lowest if the antinode of the primary wave coincides with the node of the secondary wave. The resonance distances $\bar{x}_*$ between the model and body were calculated from the equation

$$\frac{\overline{x_*}}{a(1-M)} = \frac{k}{2n} \quad (k = 1,\ 2,\ \ldots).$$

Figure 4 shows values of the relative resonance distances $\bar{x}_*$ between the model and a body of variable profile in relation to the number M_1 obtained experimentally and by calculation. By regarding the mean maximum amplitude of the base-pressure pulsations A_{max} as the sum of the amplitudes and taking A_{min} to be the difference between the mean amplitudes of the primary and secondary waves, we can obtain the mean amplitude of the primary A_1 and secondary A_2 wave for each resonance. It turns out that the profile of the body in the wake of the model has a significant effect on the amplitude of the primary and secondary pressure pulsations in the wake: a reduction in the size of the leading edge of the body causes an increase in the amplitude of the secondary pulsations from disintegration of the vortex street on the leading edge of the body. Thus, the vortex wake and the body within it are a self-exciting system, the feedback in which is provided by density waves propagating from two sources of pressure pulsations in the wake.

NOTATION

L, model length, mm; H, thickness of trailing edge of model, mm; d, diameter of cylinder, mm; h_1, plate thickness, mm; l plate length, mm; x, distance between model and body, mm; h, b, transverse dimension and longitudinal spacing of the vortex street, respectively, mm; c_V, vortex velocity, m/sec; Γ, vortex circulation, m^2/sec; $\bar{a}$, amplitude of oscillogram of density-gradient pulsations in a wake with a body behind a model; a_0, amplitude of oscillogram of density-gradient pulsations in an unperturbed wake; γ, intermittence factor of the vortex street structures; T, duration of continuous vortex street, sec; ΣT, total time of recording of vortex convergence process, sec; n, frequency of vortex convergence, 1/sec; c, flow velocity, m/sec; $\sqrt{\bar{p}^2}$, mean amplitude of pulsations in base pressure of model with a body in its wake, Pa; $\sqrt{\bar{p}_1^2}$, mean amplitude of pulsations of base pressure of model with an unperturbed wake, Pa; P_b, base pressure of model with a body in its wake, Pa; P_{b0}, base pressure of model with an unperturbed wake, Pa; $\sqrt{\bar{p}_0^2}$, mean amplitude of pressure pulsations at the forward stagnation point of a cylinder located in the model wake, Pa; $\sqrt{\bar{p}_{00}^2}$, mean amplitude of pressure pulsations at the forward stagnation point of a cylinder located outside the model wake, Pa; x_*, distance between model and a body in its wake corresponding to a resonance increase in pulsation amplitude, mm; a, speed of sound, m/sec; M, Mach number; $Re = Lc/\nu$, Reynolds number; $Sh = nH/c$, Strouhal number; $A = \sqrt{\bar{p}^2}/\sqrt{\bar{p}_1^2}$, relative amplitude of base-pressure pulsations of the model; $A_1 = \sqrt{\bar{p}_0^2}/\sqrt{\bar{p}_{00}^2}$, relative amplitude of pressure pulsations at the forward point of the cylinder; $\varepsilon = p_b/p_{b0}$, relative base pressure of model.

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UDC 536.3

Results are presented of a calculation of the heat radiation from a two-phase mixture in Laval nozzles in unidimensional and two-dimensional formulations.

The motion of a two-phase mixture in curved channels such as are present in Laval nozzles is characterized by substantial longitudinal and transverse gradients of the gasdynamic parameters in the transonic and supersonic flow regions. The radiation properties of both the gas phase and the particles of the condensed phase depend on the gasdynamic and thermodynamic characteristics of the medium. As a result, significant optical discontinuities occur both along and across the flow in Laval nozzles. Certain studies conducted in a two-dimensional approximation [1-3] show that errors may result from calculating the radiation from two-phase media in a unidimensional formulation of the problem of radiative heat transfer in the presence of substantial optical discontinuities or without allowance for the actual shape of the radiating volume.

Described below is a method of calculating the heat radiation from two-phase flows in axisymmetrical volumes with smooth diffuse-reflecting and radiating sides of arbitrary form. To describe the radiant energy transfer process, we used two-dimensional equations of the P_1-approximation of the spherical harmonics method. Calculations in a unidimensional formulation were performed in the P_3-approximation for an infinite cylinder.

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