Thus, the present study has determined the characteristics of a global detachment formed on the leading edge of a profile and encompassing practically the entire upper surface of that profile. It has been found that in the presence of an acoustical field at certain frequencies near the leading edge at the beginning of the detachment Tollmien–Schlichting waves are formed at the same frequency, leading to a significant change in the structure of the mean flow, i.e., reattachment of the boundary layer and elimination of the global detachment. It has been shown that this phenomenon exhibits hysteresis with respect to the direction in which frequency is varied.

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FLOW IN THE REGION OF INTERACTION OF AN UNDEREXPANDED LOW-DENSITY STREAM WITH A PLANE BARRIER PERPENDICULAR TO ITS AXIS

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The study of the effect of rarefaction on supersonic streams is based mainly on the results of density measurement by the method of electron-beam analysis. This method ensures that the measurement is sufficiently local in character while retaining high accuracy. Also, it does not disturb the gas flow. It has been used to conduct a broad experimental study of underexpanded streams discharged into a low-density space [1], the results obtained here having been used to then establish similarity parameters for the flows. The study [2] used data from density measurement to study the effect of rarefaction on the thickness of the Mach cone in free underexpanded streams.

Presented below are results of a study of the density distribution in a shock layer associated with an underexpanded low-density stream flowing onto a perpendicular plane barrier. We used the method of electron beam analysis in the x-ray range. The experimental data was used to evaluate the thickness of the central shock and to classify flow regimes in the shock layer according to degree of rarefaction.

1. Local density was measured using the standard system of an EOSS-2 electron gun and the recording equipment of an SSD counter. The gun was powered by a VIP-2-50-60 high-voltage source. The energy of the beam electrons was 20-25 keV, while the beam current was 1-5 mA. The energy spectrum associated with the x rays generated in the interaction of the beam electrons with molecules of the gas target was recorded with SRPO-16 and SI-12R proportional counters. The method used made it possible to measure density in the range 10^{18}-$5 \cdot 10^{21} m^{-3} \cdot sec$ with a local resolution of 1 mm^3. The total measurement error was comprised of the error of the equipment complex and the calibration error and did not exceed 15%.

Density measurement near the surface of the barrier was made considerably more complicated by the presence of background x-rays formed in the interaction of scattered electrons of the beam with the barrier material. Local values of density can be obtained in this case only

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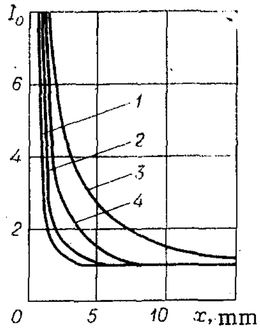

Fig. 1

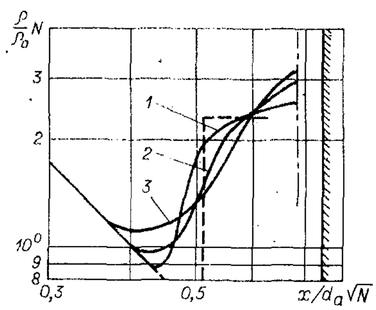

Fig. 2

with recording of the characteristic x radiation. A method of obtaining such measurements in free streams was described in [3]. According to the completed studies, the amount of background radiation depends on the degree of scattering of the beam in the gas, the distance from the beam axis to the barrier surface, and the material of the barrier. The scattering of the electron beam in turn depends on the density of the gas and the distance from the electron injector to the barrier surface. Figure 1 shows some results of measurements of background radiation in comparison with the intensity of the K_α line measured in argon, where $I_0 = I/I_\infty$, I is the radiation recorded at the surface of the barrier; I_∞ is the radiation of the gas target; x is the distance from the surface of the barrier. Curves 1-3 were obtained for barriers of graphite, aluminum, and copper, respectively, with a gas density of $5 \cdot 10^{21}$ m^{-3}. Curve 4 was obtained for a graphite barrier with a gas density of 10^{22} m^{-3}. The effect of the background radiation was alleviated by using counters with a high resolution and by using graphite and aluminum barriers, which emit low-energy x radiation under the influence of an electron beam. The experimental data was used to determine the contrast of the investigated line $m_A = N_n/N_b$ (N_n is the number of line quanta recorded by the counter, while N_b is the number of background quanta), and the results with $m_A < 10$ were excluded from examination.

2. The above-described method was used to study the flow of an argon stream onto a barrier. The stream had the following parameters: stagnation temperature $T_0 = 290$°K; Mach number at the nozzle edge $M_a = 1$; nozzle-edge diameter $d_a = 0.9$; 4.2; 5 mm; degree of expansion $N = p_0/p_\infty = 4\text{–}2 \cdot 10^4$, where p_0 and p_∞ are the stagnation pressure and the ambient pressure, respectively; the Reynolds number calculated from the parameters in the critical section of the nozzle $Re_* = 10^2\text{–}10^5$; the parameter defining the degree of rarefaction of the stream $Re_L = Re_*/\sqrt{N} = 3\text{–}10^3$.

Figure 2 shows typical results of density measurement obtained with fixed values N = 156 and a distance from the nozzle edge to the barrier $h/d_a = 9.5$ and variable values of Re_L. Curves 1-3 correspond to regimes with $Re_L = 96$; 48; 24; the dashed line shows the density distribution in an ideal gas stream, while the dot-dash line separates the measurement region in which $m_A < 10$. We took the point of inflection of the density curve as the position of the central shock. Quite evident are the differences in the evolution of the central shock compared to a shock wave ahead of blunt bodies in a uniform flow — the central shock is away from the nozzle edge, and there is an increase in density on the stream axis ahead of the central shock with an increase in the rarefaction of the stream (curves 1 and 3).

The thickness of the central shock was determined from the density measurements from the usual formula:

$$\tau = (\rho_s - \rho_c)\left(\frac{\partial \rho}{\partial x}\right)^{-1}_{\max}, \tag{2.1}$$

where ρ_c is the minimum density on the stream axis in front of the shock; ρ_s is the density after the shock.

The empirical data on the thickness of the central shock was used to check estimates obtained on the basis of the relation

$$\tau = 9.5 l_s \tag{2.2}$$

in [4] in studies of the formation of a shock wave ahead of blunt bodies in a hypersonic flow of a low-density gas. The study [2] showed the validity of this expression, which connects the thickness of the shock wave with the mean free path behind it l_s to determine the thickness of the Mach cone in underexpanded streams discharged into a low-density space. In the case of stream interaction with a barrier being examined here, analysis of the flow in the shock layer and, in particular, determination of l_s is complicated by the nonmonotonic character of the dependence of the position of the central shock on the distance h [5].

In accordance with [5], the process of interaction of dense streams with a perpendicular barrier is determined by the complex $\bar{h} = h/d_a M_a \sqrt{\gamma n}$, where $n = p_a/p_\infty$ is the off-design of the stream; p_a is the pressure at the nozzle edge; γ is the ratio of the specific heats. Three main types of interaction can be distinguished in relation to $\bar{h}$: $\bar{h} > \bar{h}_2 = (0.003 M_a^2 + 1.88) M_a^{-0.5}$ — the barrier has no effect on flow in the initial section of the stream; $\bar{h}_1 < \bar{h} < \bar{h}_2$ — the geometry of the shock-wave structure and the parameters in the shock layer depend on $\bar{h}(\bar{h}_1 = 0.32)$; $\bar{h} < \bar{h}_1$ — flow in the shock layer is independent of external conditions. For the first of these types of interactions, the thickness of the central shock can be determined from formulas for the Mach cone in a free stream: $\bar{\tau} = \tau/d_a M_a \sqrt{\gamma n} = 14/(20 + Re_L)$ [1], or $\tau = 7.6\ Kn_0 \sqrt{N}$ [2], where Kn_0 is the Knudsen number, determined from the mean free path in the prechamber and the nozzle diameter. In the case $\bar{h} < \bar{h}_2$, an expression to evaluate the mean free path in the shock layer can be obtained on the basis of the condition $l_s/l_0 = \rho_0/\rho_s$ with $T_0/T_s = 1$ by using relations for isentropic flow in the region of free expansion and relations for a forward shock. As a result, we obtain

$$\tau = c_1 Kn_0 x_c^2,$$

where $c_1 = 9.5 c^{\frac{2}{\gamma-1}} \sqrt{q(M_a)}\ \varepsilon \left(\frac{\gamma-1}{2}\right)^{\frac{1}{\gamma-1}}$; q(M) is the gasdynamic flow-rate function; $\varepsilon = \rho_c/\rho_s$ is the compression of the gas on the forward shock; the constant c determines the law of change in M(x). According to [6], at x >> 1, $M = cx^{\gamma-1}$, and the coefficient c is determined from the parameters at any point of the flow. The distance from the nozzle edge to the central shock in the case $\bar{h}_1 < \bar{h} < \bar{h}_2$ is determined from the formula $x_c = 0.745 - 0.83 \exp(-1.73\ \bar{h})$.

When $\bar{h} < \bar{h}_1$, the position of the central shock is determined from the formula in [8] for the departure of a central shock with zero geometric curvature. The expressions for τ for the investigated argon streams issuing from a nozzle with $M_a = 1$ take the form

$$\begin{gathered} \bar{h} > \bar{h}_2,\ \tau^0 = 7.6, \\ \bar{h}_1 < \bar{h} < \bar{h}_2,\ \tau^0 = 14.4[0.745 - 0.83 \exp(-1.73\bar{h})]^2, \\ \bar{h} < \bar{h}_1,\ \tau^0 = 10.65(\bar{h})^2. \end{gathered} \tag{2.3}$$

The complex $\tau^0 = \bar{\tau}/Kn_0\sqrt{N}$ represents the ratio of the thickness of the central shock to the mean free path of the molecules in the surrounding space.

It follows from Eqs. (2.3) that the thickness of the central shock depends on the rarefaction of the stream, which is determined by the parameter $Kn_0\sqrt{N}$, and on the geometry of the interaction — the value of $\bar{h}$.

The solid line in Fig. 3 shows results of calculations of the thickness of the central shock performed with Eqs. (2.3) in the investigated range of $\bar{h}$. Also shown is experimental data obtained from analysis of curves of density distribution in streams with different initial parameters d_a, N, h, and Kn_0 (points 1-3 correspond to N = 106; 384; $2 \cdot 10^4$). The good agreement seen between the calculated and experimental data throughout the range of $\bar{h}$ is evidence of the applicability of Eq. (2.2) for the investigated case of interaction of a stream with a barrier.

3. In the interaction of an underexpanded jet with a perpendicular barrier, the flow in the shock layer may change from continual to free-molecular, depending on the rarefaction of the stream and the geometry of the interaction. In the transitional region, by analogy with the classification in [4] for flow near the stagnation point ahead of blunt bodies in uniform flow, several characteristic flow regimes can be distinguished. To determine the boundaries of these regimes quantitatively, we introduce the Knudsen number in the shock layer in front of the barrier $Kn_s = l_s/\Delta$.

The effect of rarefaction in the shock layer in front of the barrier was evaluated in the range $0 < \bar{h} < \bar{h}_2$. The distance $\bar{h}_2$ is determined from the condition that the gas behind the central shock is accelerated to supersonic velocity, and a second shock wave is formed in

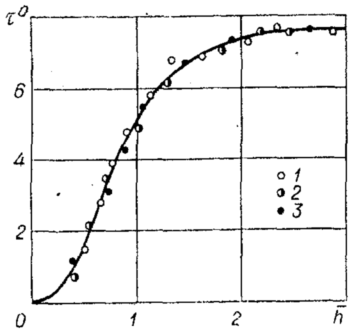

Fig. 3

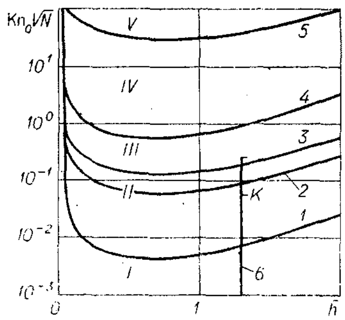

Fig. 4

front of the barrier. In this case, the shock layer, initially defined as the region of subsonic flow between the central shock and the barrier, is destroyed, and another approach is required to evaluate the effect of rarefaction in this region.

Using the connection between τ and l_s and employing Eq. (2.3) to determine τ, it is possible to obtain an expression for Kn_s as a function of the initial parameters of the interaction. Thus, for the case being analyzed $M_a = 1$ and $\gamma = 1.67$, these expressions take the form

$$\bar{h}_1 < \bar{h} < \bar{h}_2,\ \mathrm{Kn}_s = 1.53\,\mathrm{Kn}_0\sqrt{N}[(\bar{h} - \bar{\Delta})^2/\bar{\Delta}],\ \Delta = h - x_c,$$
$$\bar{h} < \bar{h}_1,\ \mathrm{Kn}_s = 1.12\,\mathrm{Kn}_0\sqrt{N}[(\bar{h})^2/\bar{\Delta}].$$

From this, assigning characteristic values for Kn_s or τ, we can find the range of interaction parameters in which a given flow regime is realized in accordance with the classification in [4].

The second parameter governing the selection of a theoretical model of flow in the shock layer is the thickness of the boundary layer on the barrier, which is determined from the expression $\delta = 2\sqrt{\langle\nu\rangle\ \beta}$ [4].

Here, $\langle\nu\rangle$ is the kinematic viscosity averaged over the thickness of the boundary layer; β is the velocity gradient of the inviscid flow at the stagnation point.

Using the analytic solution in [8] to determine the gradient in the shock layer behind the central shock, we obtain an expression for the relative thickness of the boundary layer:

$$\eta = \frac{\delta}{\Delta} = 2\sqrt{\frac{(T_w/T_0)^{\alpha}}{(1-q)\,\mathrm{Re}_s}}, \tag{3.1}$$

where q is a parameter determining the flow in the boundary layer and calculated from Eq. (2.2) in [8]; T_w is the wall temperature. Since $Re_s \sim 1/Kn_s$, $\eta \sim \sqrt{Kn_s}$ and, thus, $\tau \sim \delta^2$. consequently, both in this case and with flow about blunt bodies, the thickness of the central shock increases more rapidly than the thickness of the boundary layer as the rarefaction increases.

Having thus determined characteristic dimensions of the shock wave and boundary layer, let us proceed directly to evaluating the boundaries of the flow regimes. We take the condition $\tau/\Delta = 0.1$ ($\Delta \sim 100\ l_s$) for the existence of the continual regime with an increase in rarefaction. Here, most of the shock layer between the relatively thin shock wave and the boundary layer will be occupied by flow with equilibrium parameters. The region of the initial parameters of the interaction ensuring satisfaction of this condition is determined by substituting τ into Eq. (2.3). The results of calculations are shown in Fig. 4 (curve 1). The relative thickness of the boundary layer calculated from Eq. (3.1) is 0.09.

An increase in rarefaction leads to thickening of the central shock and the boundary layer on the barrier and contraction of the zone of inviscid flow in the shock layer. Following [4], we will assume that the inviscid zone in the shock layer disappears under the condition $0.5\ + \delta = \Delta$. Here, the position of the central shock in the first approximation is taken as constant. Calculations showed that in the case $M_a = 1$, $\gamma = 1.67$, this condition is met with $Kn_s = 0.15$, which corresponds to the values $0.5\ \tau/\Delta = 0.7$ and $\delta/\Delta = 0.3$. Thus, at the moment of joining of the central shock and the boundary layer, the thickness of the central shock is almost 5 times greater than the thickness of the boundary layer. This is confirmed by the experimental data (see Fig. 2).

In Fig. 4, the boundary of disappearance of inviscid flow is shown in the form of the line $Kn_s = 0.15$ (curve 2).

The central shock and the boundary layer overlap and change their structure with an increase in rarefaction. By analogy with [4], we take the condition $0.5\tau = \Delta$ for the beginning of decay of the central shock. The boundaries of complete disappearance of the central shock in front of the barrier will be determined from the condition $l_s = \Delta$ or $Kn_s = 1$. These boundaries correspond to curves 3 and 4 in Fig. 4. The lower boundary of the free-molecular regime is determined in [9] from the condition that the Knudsen number calculated from the mean free path of the molecules reflected from the body should be much greater than unity. Given the conditions of the experiment conducted here, this is equivalent to the condition $Kn_s = 100\varepsilon \sqrt{2\gamma/(\gamma - 1)}$. Curve 5 shows this boundary in Fig. 4. The boundaries of the regimes for $\bar{h} < 0.05$ are tentative. As a result, the entire region of the initial interaction parameters in Fig. 4 is divided into several zones corresponding to characteristic flow regimes in the shock layer which are realized with an increase in rarefaction. Zone 1 corresponds to the regime of almost continual flow about the body, where the effects of viscosity are concentrated in a thin wall boundary layer. The regime characterized by a viscous shock layer is realized in zone II. Zone III corresponds to the regime of a "disappearing shock layer." Between this regime and the free-molecular regime lie several transitional flows, where it is necessary to simultaneously consider both collisions of molecules with each other and their interaction with the surface of the barrier (zone IV). Zone V corresponds to the regime of free-molecular flow.

The study [10] presented results of an experimental study of the effect of viscosity on flow in the circulation zone in the interaction of underexpanded streams with a perpendicular barrier. It was shown that the form of the flow in the circulation zone changes with an increase in rarefaction and passes through several stages, with a radial flow being formed in front of the barrier.

Figure 4 shows the correspondence between the flow-pattern restructuring in the shock layer described in [10] and the changes in the structure of the shock wave in front of the barrier with an increase in rarefaction. The range of the investigations in [10] is shown in the form of line 6. Deformation of the circulation zone begins at $Kn_0\sqrt{N} = 10^{-3}$ and ends at $Kn_0\sqrt{N} = (6\text{-}8)\cdot 10^{-2}$ (this is shown by point K on line 6). Thus, the entire restructuring of the flow pattern described in [10] occurs in zones I and II, when the shock wave in front of the barrier can still be considered isolated.

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