We now consider the distribution of the disperse phase in the channel. The solution of Eqs. (23) and (24) for various values of $\langle\alpha_2\rangle$ shows that α_2 remains practically constant at distances from the grid greater than two or three granule diameters. At smaller distances from the grid for a channel of sufficient radius $[(R_2 - R_1)/2a > 6]$ the solution predicts a decrease in α_2. However, the investigated model does not allow for processes near the grid, viz., the variation of the fluctuation velocities, inflow, and repulsion of the granules, etc. Consequently, the problem of the behavior of the granules near the grid requires additional investigation.

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FORMATION OF FLOW IN A GASDYNAMIC MOLECULAR SOURCE AT LOW REYNOLDS NUMBERS

V. N. Gusev and A. I. Omelik

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1. The usual means of creating a molecular beam in a gasdynamic source [1] is shown in Fig. 1. From the forechamber 1 the gas, with a pressure p_0 and a temperature T_0, expands through the nozzle 2 to a certain supersonic Mach number in the preskimmer chamber 3 ($0 \leq x \leq x_s$). In the process, a considerable part of the chaotic thermal motion of the molecules is converted into ordered mass motion. In the high-vacuum chamber 4 ($x > x_s$) a small part of this stream is subsequently formed into a molecular beam with the help of a conical intake — the skimmer 5; 6 is the boundary of the undisturbed region of the jet, 7 is a suspended shock, and 8 is the boundary of the jet.

For a Maxwell velocity distribution of the molecules with a superposed mass velocity v_m the intensity of such a source at the detection point x_d is [2]

$$I(x_d) = \rho(x_d) v_m x_d^2 = I(x_s)\left\{1 - \cos^2\psi e^{-S_s^2 \sin^2\psi} \frac{I_1(S_s \cos\psi)}{I_1(S_s)}\right\},$$

$$I_1(x) = \frac{1}{2} e^{-x^2} + \frac{x\sqrt{\pi}}{2}(1 + \operatorname{erf} x),$$

where ρ is the density; $S = (\sqrt{\kappa/2})M = v_m(2RT)^{-1/2}$ is the velocity ratio; κ is the ratio of specific heats; $\psi = \varphi + \gamma$. For small angles ψ, as is usually the case in such installations, the latter expression is simplified,

$$I(x_d) = I(x_s)\left[1 - e^{-\psi^2 S_s^2}\right] \tag{1.1}$$

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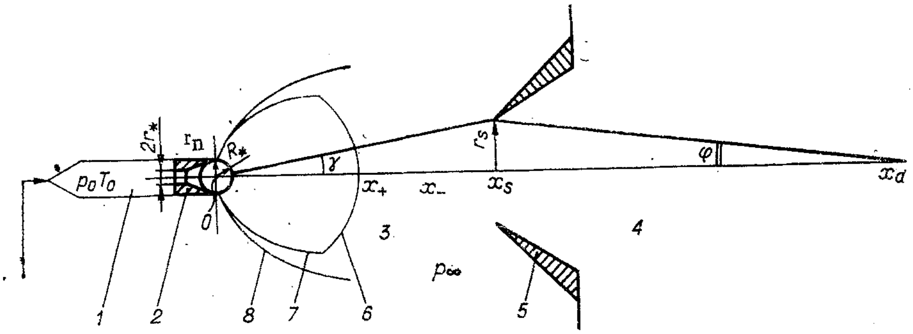

Fig. 1

and determines the losses of intensity of a gasdynamic source in comparison with a quasispherical one. The dependence of $\bar{I}(x_d) = I(x_d)/I(x_s)$ on ψS_s is given by a solid line in Fig. 2a. The intensity of a gasdynamic source will be greatest for $\psi S_s \geqq 2$.

We note that for $\psi S_s \ll 1$,

$$I(x_d) = \psi^2 S_s^2 I(x_s)$$

and for $S_s \gg 1$ and $\gamma \ll \varphi \ll 1$ the expression for the intensity of a gasdynamic source following from Eq. (1.1) will coincide with that obtained earlier in [3],

$$I(x_d) = \varkappa\rho(x_s)\, v_m M_s^2 r_s^2/2,$$

where r_s is the radius of the skimmer; $v_m = (\sqrt{(\kappa+1)/(\kappa-1)})v_* = \sqrt{2\kappa RT_0/(\kappa-1)}$ is the limiting velocity.

As a rule, the pressure p_∞ in the preskimmer chamber is considerably lower than the pressure p_n at the nozzle cut. In this case the gas expansion occurs in a highly underexpanded jet up to the rarefaction wave centered at the exit rim of the nozzle. The flow inside the jet is fully determined by the assignment of the initial data in the exit cross section of the nozzle. Along the jet axis the flow asymptotically approaches the flow from a certain axisymmetric source, the radius of the critical cross section of which is $R_* = R_*^0(0)r_*$, where r_* is the radius of the critical cross section of the nozzle.

To clarify the overall pattern of flow, we consider the limiting regime of infinitely high Reynolds numbers. In this case, the flow inside the highly underexpanded jet, independent of the external conditions, will be bounded geometrically by the suspended compression shocks and the Mach disk. The position of the latter at the axis of symmetry is determined by the equation

$$x_+/r_n = \alpha(M_n, \varkappa)\sqrt{p_0/p_\infty}, \tag{1.2}$$

where r_n and M_n are the radius of the exit cross section of the nozzle and the Mach number in this cross section. The size of the supersonic region of flow will increase without limit as the pressure drop p_0/p_∞ increases. The values of $R_*^0(0)$ for different values of M_n and κ, needed to determine the stream parameters in this region, were obtained on the basis of numerical calculations by the method of characteristic curves and are presented in [4].

Since the flow behind the Mach disk becomes subsonic, in the formation of a molecular beam in a gasdynamic source using a highly underexpanded jet the position of the skimmer must be determined from the condition $x_s < x_+$, and the radius of its opening must be determined from the condition of free-molecule streamline flow $r_s \ll \lambda_s$, where $\lambda_s = (4/5\sqrt{\kappa})(\mu_s/\rho_s a_s)$, a is the speed of sound, and μ is the viscosity coefficient. For the regime under consideration the value of λ_+ is considerably less than the characteristic size x_+.

For a Reynolds number $Re_* \to \infty$ and a degree of dependence of the viscosity coefficient on temperature $\mu \sim T^n$, from the condition $r_s \ll \lambda_+$ we get

$$\gamma S_s \ll \frac{1}{\mathrm{Re}_*}\left(\frac{x_+}{R_*}\right)^{2\varkappa-1-2n(\varkappa-1)}$$

or, with allowance for (1.2),

$$\gamma S_s \ll \frac{1}{\mathrm{Re}_*}\left(\alpha\sqrt{\frac{p_0}{p_s}}\right)^{2\varkappa-1-2n(\varkappa-1)}, \quad \mathrm{Re}_* = \frac{\rho_* v_* R_*}{\mu_*}. \tag{1.3}$$

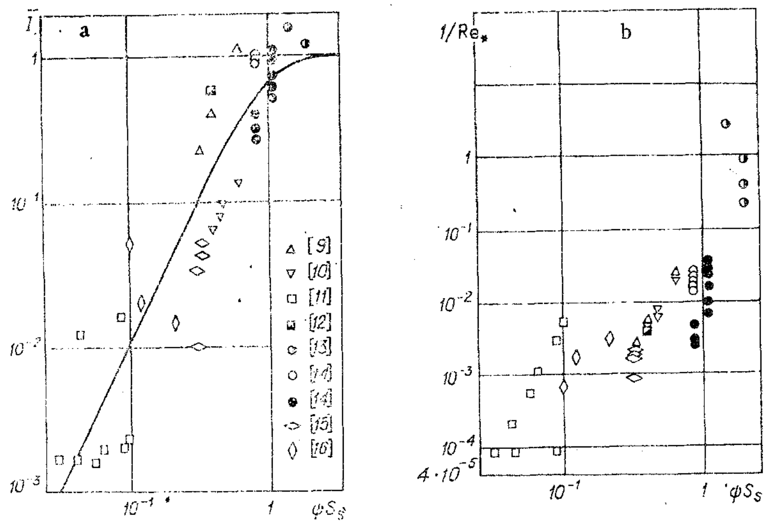

Fig. 2

From the latter inequality it is seen that no matter how high the value of Re_*, one can always choose a pressure drop p_0/p_∞ for which the intensity of the gasdynamic source will be greatest ($\gamma S_S > 2$). For high Re_*, however, the required pressure drops here are so large that it may prove impossible to realize such regimes. On the other hand, as follows from the inequality (1.3), the maximum stream intensity in a gasdynamic source can be realized through a decrease in Re_*. This was pointed out in [5] on the basis of an analysis of numerous experimental data of various authors. Since the flow pattern in a jet varies considerably with a decrease in Re_*, we shall consider flow regimes in a gasdynamic molecular source at low values of Re_*.

2. A detailed analysis made in [6, 7] on the basis of a numberical solution of the Navier–Stokes equations showed that for a finite value of Re_* the supersonic region, not dependent on the external conditions, remains bounded ($\bar{x} < \bar{x}_+$) with an unlimited increase in the pressure drop p_0/p_∞ and decreases with a decrease in Re_*. In its hypersonic part, the following asymptotic expressions [8] are valid for the velocity $\bar{v} = v/v_*$, the density $\bar{\rho} = \rho/\rho_*$, the temperature $\bar{T} = T/T_*$, and the pressure $\bar{p} = p/p_*$:

$$\bar{v} = \sqrt{\frac{\varkappa+1}{\varkappa-1}} + W\mathrm{Re}^{-\lambda},\ \bar{\rho} = \sqrt{\frac{\varkappa-1}{\varkappa+1}}\left(1 - \sqrt{\frac{\varkappa-1}{\varkappa+1}}\,W\,\mathrm{Re}^{-\lambda}\right)\bar{x}^{-2},$$
$$\bar{T} = \Theta\mathrm{Re}^{-\lambda};\ \bar{p} = \sqrt{\frac{\varkappa-1}{\varkappa+1}}\,\Theta\mathrm{Re}^{-\lambda}\bar{x}^{-2}, \tag{2.1}$$

where

$$\Theta = \left\{\frac{\varkappa(\varkappa+1)(1-n)\,\omega}{X} + \left(\frac{\varkappa-1}{\varkappa+1}\right)^{\frac{(\varkappa-1)(1-n)}{2}} X^{2(\varkappa-1)(1-n)}\right\}^{\frac{1}{1-n}};$$
$$W = -\frac{\Theta}{\sqrt{(\varkappa+1)(\varkappa-1)}} - \sqrt{\frac{\varkappa+1}{\varkappa-1}}\,\frac{\Theta^n}{X};$$
$$X = \bar{x}^{-1}\mathrm{Re}^{\omega};\ \bar{x} = \frac{x}{R_*};\ \mathrm{Re} = \frac{3}{4}\mathrm{Re}_*;\ \lambda = 2(\varkappa-1)\,\omega;$$
$$\omega = [2\varkappa - 1 - 2(\varkappa-1)n]^{-1}.$$

In this case the extent of the supersonic flow region not dependent on the external conditions is determined by the coordinate $\bar{x}_+$ at which the stream parameters (2.1) reach the extremal values [7]:

$$\bar{x}_+ = \left(\frac{2}{\varkappa\omega}\right)^{\omega}\left(\frac{\varkappa-1}{\varkappa+1}\right)^{\frac{3\omega+1}{4}}\mathrm{Re}^{\omega}. \tag{2.2}$$

In this cross section the maximum value of the Mach number is

$$M_+ = \frac{v_+}{\sqrt{\varkappa R T_+}} = \sqrt{\frac{\varkappa+1}{(\varkappa-1)\Theta_+}}\,\mathrm{Re}^{\frac{\lambda'}{2}} \tag{2.3}$$

and the hypersonic mean free path of the molecules becomes comparable with the characteristic size of the flow region undisturbed by the external conditions:

$$\lambda'_+ = M_+\lambda_+ \approx \frac{\mu_+ v_+}{a_+\rho_+\sqrt{T_+}} \approx \frac{\bar{x}_+\bar{T}_+^{n-1}}{\mathrm{Re}}\,x_+ \approx \mathrm{Re}^{\omega-1-\lambda(n-1)}x_+ \approx x_+.$$

With allowance for the latter estimate, from the condition $r_S \ll \lambda'_+$ we get $\gamma S_+ \ll M_+ \approx \mathrm{Re}^{\lambda/2}$. Since

$$\frac{p_+}{p_*} = \sqrt{\frac{\varkappa-1}{\varkappa+1}}\,\Theta_+ X_+^2\,\mathrm{Re}^{-2\varkappa\omega}, \tag{2.4}$$

for low Re (in contrast to high values) the maximum intensity of a gasdynamic source ($\gamma S_+ > 2$) can be realized at moderate pressure drops. The limiting values of the intensity $I(x_d^+) = 1$ in gasdynamic sources are presently obtained only at relatively low Reynolds numbers. This conclusion is supported by the experimental data of various authors presented in Fig. 2.

With a further decrease in Re the supersonic region decreases until the flow becomes subsonic everywhere. In the limiting case (Re → 0) the effusional regime of escape of gas from the nozzle sets in.

As already mentioned, at the boundary of the undisturbed region the hypersonic mean free path of the molecules is $\lambda_+ \approx x_+$. At such a level of rarefaction in the jet the compression shocks disappear and molecules of the ambient medium at $x > x_+$ start to diffuse into the jet. At finite pressures $p_\infty < p_+$ the flow in the region $x < x_+$ remains unchanged.

The existence of this regime was first pointed out in [17] and an approximate analysis of it was given in [18]. This regime was investigated experimentally at high temperatures in [14, 19].

We determine the density variation along the jet axis at $x > x_+$ on the basis of the following model. Let collisions between molecules in the stream be confined to the region of $x < x_+$. Then at $x > x_+$ the density distribution in an expanding stream propagating in the residual gas is determined from the equation

$$\frac{d\rho}{\rho} = -\left(\frac{1}{\lambda} + \frac{2}{x}\right)dx,$$

where $\lambda = m_\infty/\sigma\rho_\infty$; σ is the collision cross section; m_∞ is the mass of a molecule. The quantity λ is determined by the density of the residual gas penetrating into the jet. Such penetration (diffusion) takes place gradually at $x > x_+$. In schematizing the flow, we shall assume that collisionless dispersion of the gas occurs at $x_+ < x < x_-$, while at $x_- < x < x_S$ the pressure of the residual gas inside the jet reaches its value outside the jet. The quantity $x_S - x_-$ will be determined below under this assumption.

The following relations are valid for the region $x_+ < x < x_-$:

$$\bar{v} = \bar{v}_+ = \sqrt{\frac{\varkappa+1}{\varkappa-1}} + W_+\mathrm{Re}^{-\lambda},\quad \bar{\rho} = \sqrt{\frac{\varkappa-1}{\varkappa+1}}\left(1 - \sqrt{\frac{\varkappa-1}{\varkappa+1}}W_+\mathrm{Re}^{-\lambda}\right)\bar{x}^{-2},$$
$$\bar{T} = \bar{T}_+ = \Theta_+\mathrm{Re}^{-\lambda},\quad \bar{p} = \sqrt{\frac{\varkappa-1}{\varkappa+1}}\,\Theta_+\mathrm{Re}^{-\lambda}\bar{x}^{-2}. \tag{2.5}$$

In contrast to a source with a fixed value of Re, here the temperature $\bar{T}$ is constant while the pressure $\bar{p}$ varies in inverse proportion to $\bar{x}^2$. It should be noted that the specific flow rate in the entire region of $x < x_-$ is

$$\bar{\rho}\bar{v} = \bar{x}^{-2} + O(\mathrm{Re}^{-2\lambda}).$$

In contrast to the other flow parameters, the law of variation of the specific flow rate remains constant, to within the indicated accuracy, with variation of the Reynolds number.

At $x > x_-$ collisions of molecules of the jet with molecules of the ambient gas become dominant. Here the values of the stream parameters will approach monotonically to the corresponding values in the ambient space.

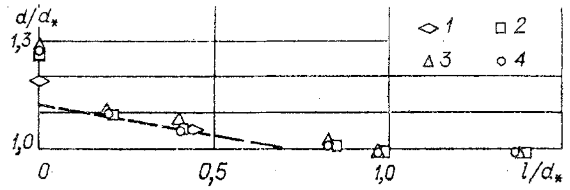

Fig. 3

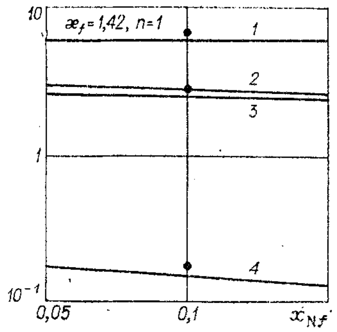

Fig. 4

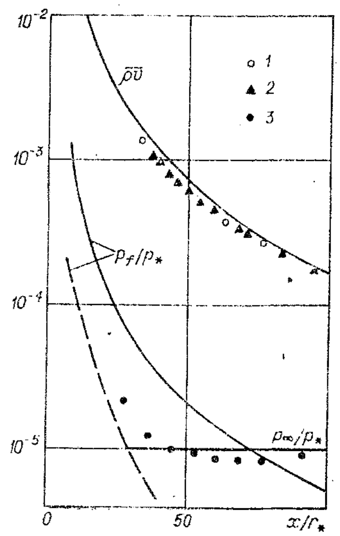

Fig. 5

3. The regime of flow in a gasdynamic source considered above becomes primary in the modeling of the conditions of aircraft flight in the free-molecule region [20]. Here the main requirements come down to an increase in the stream velocity to a value comparable with the flight velocity, to an increase in the stream intensity to a value providing for the modeling of adsorption conditions at a surface, to an increase in the size of the core of the flow for tests of models of complicated shape, and to a decrease in the measurement errors. According to the analysis made above, all these requirements can be satisfied only at low Reynolds numbers.

An example of the accomplishment of such a regime is the installation of [14]. Nitrogen at a pressure $p_0 = 4 \cdot 10^4$ Pa is used as the working gas in it. High-frequency heating is used to increase the stream velocity, while a large-diameter skimmer ($r_S/r_* = 14.2$) is used to obtain a molecular stream of high intensity with a large cross section.

In the main working regime the stagnation temperature, determined by the flow-rate method, is $T_0 = 5600$°K. The equilibrium values of the stream parameters in the critical cross section corresponding to it are: pressure $p_* = 2.3 \cdot 10^4$ Pa, density $\rho_* = 1.31 \cdot 10^{-2}$ kg/m³, temperature $T_* = 5340$°K, velocity $v_* = 1380$ m/sec, viscosity coefficient $\mu_* = 135 \cdot 10^{-6}$ N·sec/m², molecular weight $m_* = 26$, molar concentration of atomic nitrogen $x_{N*} = 0.144$, frozen-in value of the ratio of specific heats $\kappa_{*f} = (7 - 2x_{N*})(5 - 2x_{N*})^{-1} = 1.42$.

A sonic nozzle, which is made in the form of a short cylindrical channel, is usually used in gasdynamic sources. Burnout of the channel occurs at high temperatures, however, leading to a change in its shape. This change in our case is presented in Fig. 3, where the dashed line is the initial shape of the channel, $d_* = 1.203$ mm; 1) shape of the channel after 6 h of operation, $d_* = 1.203$ mm; 2) after 12 h of operation, $d_* = 1.203$ mm; 3) after 18 h of operation, $d_* = 1.208$ mm; 4) after 24 h of operation, $d_* = 1.230$ mm. The established channel profile is characterized by a ratio of radii $r_n/r_* = 1.33$. For such a supersonic nozzle the value of $Re_*^0(0)$ determining the radius of the critical cross section of the equivalent source is 1.3 [4], and it corresponds to $Re_* = 105$.

The presence of an expanding section of the channel leads to a decrease in the gradients of the stream parameters in the initial section of the jet. This increases the monochromaticity of the stream and, for a finite degree of dissociation, its velocity.

The high-temperature flow regime ($T_0 = 5600$°K) in the installation under consideration requires allowance for the actual properties of the gas in addition to the viscosity. The

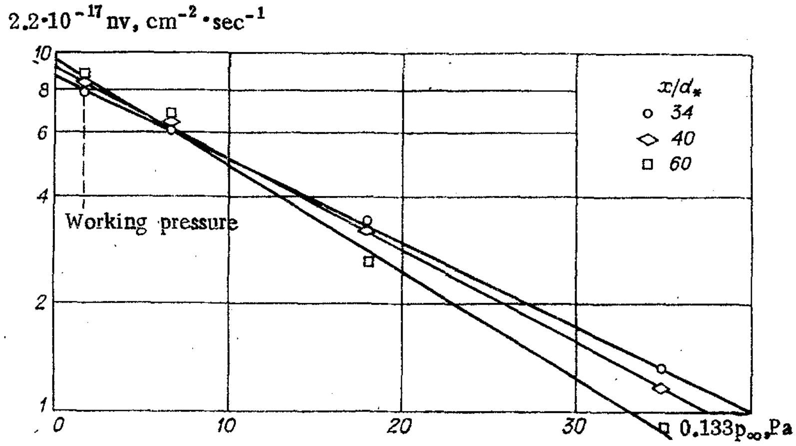

Fig. 6

problem was analyzed above for an ideal gas. The flow parameters in the part of the jet not dependent on the external conditions are determined by Eqs. (2.1). The same expressions can be used for the frozen-in values of the stream parameters in the method of instantaneous freezing-in. For the limiting values of the velocity and temperature, for example, we will have

$$\frac{v_{+f}}{v_{*f}} = \frac{v_+}{v_*},\quad \frac{T_{+f}}{T_{*f}} = \frac{T_+}{T_*}\quad \text{or}\quad \frac{v_{+f}}{v_*} = \frac{v_+}{v_*}\frac{v_{*f}}{v_*},\quad \frac{T_{+f}}{T_*} = \frac{T_+}{T_*}\frac{T_{*f}}{T_*}.$$

The first of the ratios appearing in these expressions are determined from (2.1) and are functions of Re_*, κ_{*f}, and x_{N*}, which depend on the frozen-in value of the molar concentration x_{Nf}. For $Re_* = 105$, $\kappa_{*f} = 1.42$, and $n = 1$, when the flow is frozen in by composition in the critical cross section of the nozzle, the extent of the supersonic region of the jet (2.2) not dependent on the external conditions is $x_+/r_* = \bar{x}_+ R_*^0(0) = 25$, while the limiting values of the velocity and temperature at this point, determined from (2.1), are $v_+/v_* = 2.19$ and $T_+/T_* = 0.134$.

The frozen-in values v_{+f}/v_* and T_{+f}/T_* corresponding to them are presented in Fig. 4 as functions of the molar concentration x_{Nf} (lines 3 and 4). Here for comparison we give the quantity v_{mf}/v_* (line 2), determined by the method of instantaneous freezing-in without allowance for viscosity. The difference between v_{mf}/v_* and v_{+f}/v_* is slight in the entire range of variation of the molar concentration x_{Nf}. The variation of the Mach number M_{+f} is also given there (line 1). Just like the viscosity, the nonequilibrium processes have a weak influence on the distribution of the specific flow rate $\bar{\rho}\bar{v}$ along the jet axis ($\bar{\rho}_f\bar{v}_f \approx \bar{\rho}\bar{v}$).

The penetration of molecules of the ambient gas into the jet begins at $x > x_+$. In our case, the frozen-in value of the pressure in the cross section $x = x_+$,

$$p_{+f} = p_*(p_+/p_*)(p_{*f}/p_*),$$

determined using (2.4), proves to be considerably higher than the pressure p_∞ in the preskimmer chamber and, in accordance with the adopted flow scheme, the regime of scattering of the jet can be preceded by the collisionless dispersion of the gas. For an ideal gas the stream parameters in the region of dispersion are determined from Eqs. (2.5). Here the velocity and temperature are constant. Stabilization of the temperature at $x > x_-$ was recorded in an experiment on the installation of [14] in a measurement of the rotational temperature [21].

The other variables in the region of dispersion remain functions of the coordinate x/r_*. The variation of the specific flow rate $\bar{\rho}\bar{v}$ and the frozen-in value of the pressure p_f/p_* are presented in Fig. 5 for $x_{Nf} = 0.1$ (solid lines). As already noted, neither the viscosity nor the actual properties of the gas influence the distribution of the specific flow rate in the jet in the region of dispersion, and the integral $\bar{\rho}\bar{v}x^2 = 1$ remains valid here. The latter fact was noted in [19] on the basis of experimental research. Data borrowed from it, reduced to the determining parameters adopted in the present work, are given in Fig. 5 (points 1 and 2).

The viscosity and the actual properties of the gas have a significant influence on the pressure distribution in addition to the temperature. The pressure in the jet in the region of dispersion is also considerably higher than the corresponding pressure in one-dimensional isentropic expansion of the gas (dashed line in Fig. 5). The results of pressure measurements using a static-pressure probe also point to this fact (points 3). Without the appropriate introduction of corrections, the pressure measured in the experiment cannot be interpreted as static. However, the character of its variation can be used to estimate the extent of the region of scattering of the jet. The comparison of the experimental and calculated values of p_f/p_* with the pressure of the residual gas in the preskimmer chamber, p_∞/p_*, presented in Fig. 5, shows that scattering can begin at $x/r_* > 50$, when $p_- \leqq p_\infty$. To determine the amount of this scattering in the working chamber of the installation ($x = x_d$) we measured the mass fluxes of the molecular beam for different values of the pressure in the preskimmer chamber.

The loss of intensity of a molecular beam in the working part of a gasdynamic source due to weak scattering in the preskimmer chamber is determined by the expression $I(x_d) = I(R_*) \exp(-\sigma\rho_\infty(x_s - x_-)/m_\infty)$.

For constant values of $I(R_*)$, x_d, and σ, the effective scattering length (if $x_s - x_-$ does not depend on p_∞) is

$$(x_s - x_-) = -\frac{kT_\infty}{\sigma}\frac{d\ln(nv)}{dp_\infty},$$

where $n = \rho/m$; k is the Boltzmann constant.

The results of this experimental investigation on the determination of the effective scattering length are presented in Fig. 6. For $\sigma = (1\text{-}4)\cdot 10^{15}\,\text{cm}^2$ [24] its value $(x_s - x_-)/r_*$ varies in the range of 10-30. The initial coordinate of beam scattering corresponding to these values is $x_-/r_* = 50\text{-}80$, while the losses of beam intensity due to scattering at $x_s/r_* < 100$ do not exceed 7-8%. With such relatively small intensity losses, the theoretical values of v_{+f}, T_{+f}, and M_{+f} determined above also remain unchanged in the working chamber of a gasdynamic source at $x = x_d$. Measurements [14, 22, 23] made in this region (points in Fig. 4) agree sufficiently well with them.

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EXPERIMENTAL STUDY OF HEAT FLOWS IN THE WALLS OF A HIGH-ENTHALPY MHD CHANNEL

V. I. Alferov, O. N. Vitkovskaya, A. P. Rudakova,
A. D. Sukhobokov, and G. I. Shcherbakov

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There is currently considerable interest in the study of high-enthalpy MHD channels such as in MHD accelerators and MHD generators with a high unit energy removal. One of the most important factors determining the possibility of operating such equipment successfully is the limiting value of the heat flux in their walls. Theoretical analysis of heat-transfer processes under these conditions is very difficult due to their complexity. The most reliable data can be obtained mainly in experiments. Test data on heat transfer is also useful to explain features of gas flow in MHD units.

The present article reports results of experimental studies of local heat flows in the walls of an MHD channel during different regimes of its operation. Special attention was given to aspects of the reliability of measurement of heat flow to B-walls.

1. Experimental Method. Tests were conducted on a unit consisting of a Faraday MHD channel with sectional electrodes operating in the accelerator regime.

Figure 1 shows a basic diagram of the unit. Air heated in an electric-arc heater 1 and saturated with an easily-ionized addition agent 2 in a mixing chamber 3 is discharged through

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