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LOCAL FORCE LOADS FROM A SUPERSONIC UNDEREXPANDED STREAM ON A FLAT SURFACE PARALLEL TO THE STREAM AXIS

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The action of the force of a stream with a large degree of nonsimilarity ($n = 2\cdot10^1$–$8\cdot10^4$) on a flat surface, displaced from the nozzle axis at distances $h = h/r_a = 2$–10, is studied experimentally for an interaction region along the flow line for Reynolds numbers $Re_* = 1.7\cdot10^3$–$2.1\cdot10^4$ (the Reynolds number is determined according to the parameters in the critical cross section). The working fluids consist of argon, air, and propane, flowing from conical nozzles with an aperture half-angle at the exit $\theta_a = 10°$ and the ratio of the diameters of the exit and critical cross sections $\xi = d_a/d_* = 1.0$–4.8. A simple empirical dependence is suggested, as a result of this work, for the determination of the location of the second maximum of the force loads and their maximum magnitudes. A universal profile is presented for the pressure along the flow line.

The interaction between a supersonic underexpanded stream and a flat surface parallel to the stream axis is accompanied by the formation of a complex shock wave structure with the presence of a large number of gasdynamic explosions, as well as subsonic and supersonic flow regions. A rigorous analytic solution is hardly possible for the problem. At the same time, such problems are solved by using numerical [1-4] as well as approximate methods [5-9].

The errors involved in these methods can attain significant magnitudes, while the calculations can be quite laborious. In addition, in engineering, it is often necessary to estimate the magnitudes of the force loads on a flat surface interacting with a supersonic underexpanded stream, the parameters of which vary over a wide range of values. In the present work, simple dependences are obtained on the basis of the results of experimental research for calculating the force loads along the flow line in the interaction region.

The experiments were performed in the stationary regime in a low-density gasdynamic tube equipped with a nitrogen cryogenic pump [10]. The residual pressure in the working volume of the vacuum chamber in these experiments varied over the range $1\cdot10^{-3}$–$1\cdot10^{-2}$ mm Hg ($1.33\cdot10^{-1}$–1.33 Pa) and was measured by a PMT-2 transducer on a VT-3 vacuum gauge. The source of the supersonic stream was a heated receiver with a replaceable conical nozzle, having a half-angle at the exit $\theta_a = 10°$ and a ratio of diameters at the exit and critical cross sections given by $\xi = d_a/d_* = 1.0$; 1.3; 2.0; 3.25; 4.8.

Argon, air, and propane were used as the working fluids. Their mass flow rates varied in the range 0.07–0.75 g/sec. The deceleration pressure p_0 varied over the range 0.25 kg/cm² ($2.45\cdot10^4$ Pa)–2.1 kg/cm² ($2.06\cdot10^5$ Pa), the deceleration temperature varied over the range $T_0 = 400$–$1000°K$, and the Reynolds number, determined from the parameters in the critical cross section of the nozzle, attained the values $Re_* = 1.7\cdot10^{-3}$–$2.1\cdot10^4$. The degree of nonsimilarity flow as a function of the type of gas, Mach number at the edge of the nozzle, deceleration parameters, and pressure in the vacuum chamber varied over the range $n = 2\cdot10^1$–$7.8\cdot10^4$.

The basic results concerning the location of the maximum loads as a result of the interaction between a supersonic stream with a large degree of nonsimilarity and a contiguous flat surface were obtained using heat-sensitive coatings. A thin layer of heat-sensitive melting indicator coating (TI-65, TI-120) was placed on the surface of a plate made of a thermally insulating material. The material $T_* < T_e$ was satisfied in all the experiments

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(the temperature of the phase transition is less than the temperature for reducing the gas in the boundary layer). The prepared plate was placed at a definite distance from the axis of the nozzle with the help of a coordinate setup. The location of the maximum of the loads was determined from the region of the heat-sensitive coating that melted first. For convenience in analyzing the results, a coordinate grid was drawn on the surface of the plate. The absolute error of the measurements did not exceed ±1.0 mm, which corresponded to $\pm(0.3-0.9)r_a$ depending on the geometrical properties of the nozzles.

The magnitudes of the local force loads in the interaction region were studied with the help of a PMT-2 thermocouple gauge on the VT-3 vacuum gauge, calibrated with a McLeod gauge and a U-shaped dibutylphthalate gauge. The latter was used for measuring the pressure at small distances separating the nozzle axis from the surface. The total error in the measurements did not exceed 10%.

As is well known, when a supersonic underexpanded stream interacts with a contiguous surface there can arise regimes in which two maxima are observed in the local force loads on the surface. The first maximum, closest to the nozzle exit, results from the interaction of the compressed layer with the surface, while the second maximum results from the nonuniformity in the positioning of the angles of inclination of the flow field. The position of the second maximum in the local force loads for a large degree of nonsimilarity does not depend on the conditions in the surrounding medium and is determined by the nature of the distribution of the parameters at the center of the stream. Two basic factors influence the distribution of the parameters at the center of the stream: the type of working fluid or the ratio of the heat capacity of the fluid and the geometric characteristics of the nozzle from which the flow emanates. Figure 1 (p_0 = 0.2-0.4 kg/cm² = $1.96\cdot10^4$-$3.92\cdot10^4$ Pa, T_0 = 590-770°K, $Re_* = 1.7\cdot10^3$-$3.2\cdot10^3$) shows the experimental data reflecting the dependence of the position of the second load maximum on the distance between the axis of the sonic nozzle and the surface for different working fluids, while Fig. 2 shows the same for a propane stream and a nozzle with different ratios of the exit and critical cross section diameters (C_3H_8; p_0 = 0.25 kg/cm² = $2.45\cdot10^4$ Pa, T_0 = 650°K, $Re_* = 3.2\cdot10^3$). As the ratio of the exit and the critical cross section diameters of the nozzle $\xi = d_a/d_*$ increases, while the distance between the nozzle axis and the surface $\bar{h} = h/r_a$ (r_a is the radius of the exit cross section of the nozzle) remains the same, the distance to the second load maximum, measured from the nozzle exit, increases. Similar results are obtained for the other working fluids (air, carbon dioxide, argon). The experimental data were approximated using the method of least squares as a power law with the help of multiple linear regresssion on a ES computer

$$\bar{x}_m = 0.48\gamma^{1.52}\xi^{0.37}\bar{h}^{1.1}, \tag{1}$$

where $\gamma = c_p/c_V$ is the ratio of the heat capacities of the working fluids; $\xi = d_a/d_*$ is the ratio of the diameters of the exit and critical cross sections; $\bar{h} = h/r_a$ is the relative distance between the nozzle axis and the surface; $\bar{x} = x/r_a$ is the relative coordinate of the second load maximum measured from the nozzle exit.

In the general case, the position of the second load maximum depends on the regime of the flow from the nozzle and the regime of the interaction with the plate. The nature of the distribution of the force loads and its quantitative characteristics, in particular, depend on the manifestation of viscous effects in the nozzle (increase in the boundary layer in the nozzle, leading to a change in the effective parameters at the nozzle exit), in the region of free expansion and with the interaction with the surface (on shock waves and in the compressed layer). As the Reynolds number decreases, losses increase in the shock wave structure, the overall picture of the flow becomes more diffuse, and the properties of the boundary layer at the surface of the barrier change. The manifestation of the effects indicated above (with decreasing Reynolds number Re_*) leads to a decrease in the magnitude of the second load maximum and it shifts downwards along the flow.

In the range $Re_* = 10^3$-$2\cdot10^4$, the influence of the boundary layer on the characteristics of the nozzle is insignificant and depending on the length of the nozzle does not exceed 10%. At the same time, in the indicated range of Re_*, the losses due to viscous dissipation mentioned above, which change the picture of the flow at the flat surface and cause the force loads to change, become significant. Taking into account the boundary layer in the nozzle and the regime of the interaction with the plate and the range $Re_* = 10^3$-$2\cdot10^4$, the function (1) can be refined as follows:

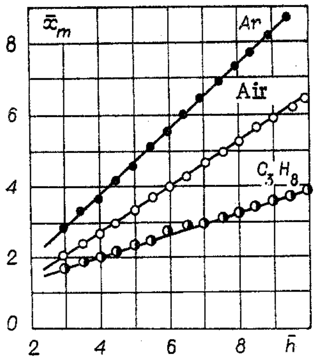

Fig. 1

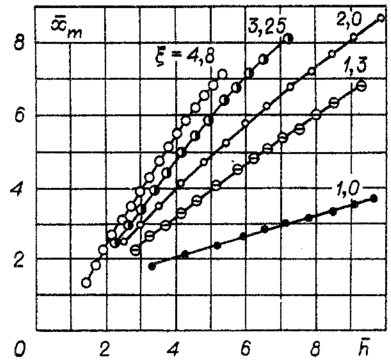

Fig. 2

$$\bar{x}_m = 1.578\gamma^{1.52}\xi^{0.37}\bar{h}^{1.1}(\lg \mathrm{Re}_*)^{-1}. \tag{2}$$

In the range of values for initial data $\xi = 1.3\text{-}4.8$; 1.10-1.67 and $\bar{h} = 1.5\text{-}12.0$, the relative error in the approximation does not exceed 12%. Figure 3 shows a generalization of the experimental data in terms of the approximating function (1) ($\mathrm{Re}_* = 10^3\text{-}2\cdot10^4$).

Figure 4 shows the results of measurements of the pressure along the flow line on a flat surface for a supersonic nozzle with $\xi = 4.8$ for different distances between the nozzle and the surface ($\mathrm{Re}_* = 2\cdot10^3$). As the distance between the stream axis and the flat surface increases, the magnitudes of the second pressure maximum decrease sharply (Fig. 4a) and, at the same time, the acceleration of the stream flow from the nozzle exit also drops, which is indicated by the intersection of the pressure profiles (Fig. 4b).

The dependence of the maximum pressures $\bar{p}_m = p_m/p_0$ in the interaction region on the magnitudes of the displacement $\bar{h}$ for different degrees of expansion of the nozzle ξ is shown in Fig. 5 ($\mathrm{Re}_* = 1.7\cdot10^3$). The data obtained were approximated by a power law in the range $\mathrm{Re}_* = 10^3\text{-}2\cdot10^4$:

$$\bar{p}_m = 0.051\xi^{-2.6}\bar{h}^{-1.6}\mathrm{Re}_*^{0.17}. \tag{3}$$

The relative error in the approximation did not exceed 18%. Fig. 5 shows a comparison of the function (3) (solid line) with the experimental data. Analysis of the distribution of pressure along the flow line showed that for the same nozzle the longituidinal pressure profiles for different displacements $\bar{h}$ are the same, if the analysis is performed at the coordinates x/x_m and p/p_m, where x_m and p_m are the characteristics of the load maximum, the coordinate and pressure, respectively; x and p are the instantaneous values of the profile coordinate and pressure, respectively.

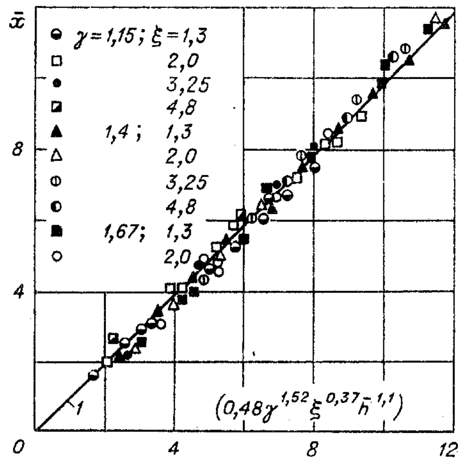

Fig. 3

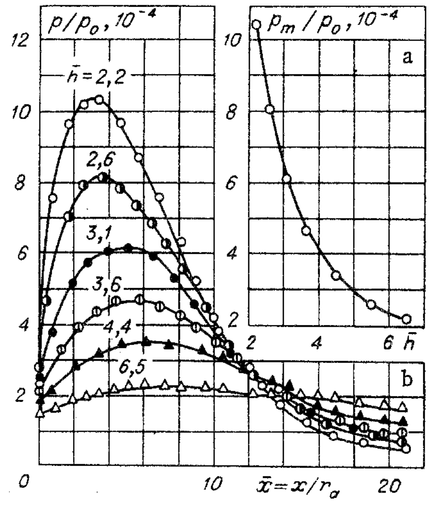

Fig. 4

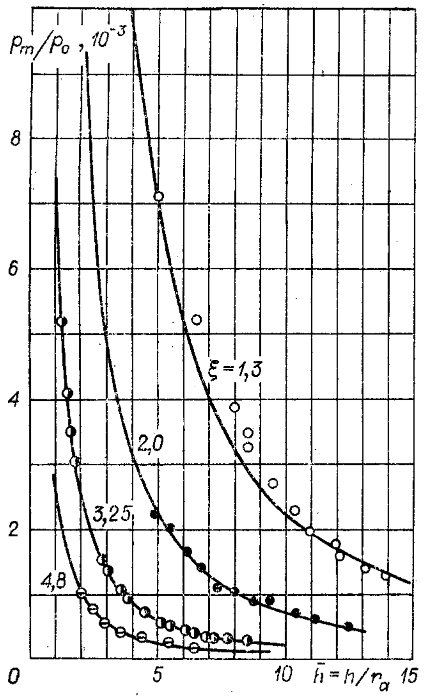

Fig. 5

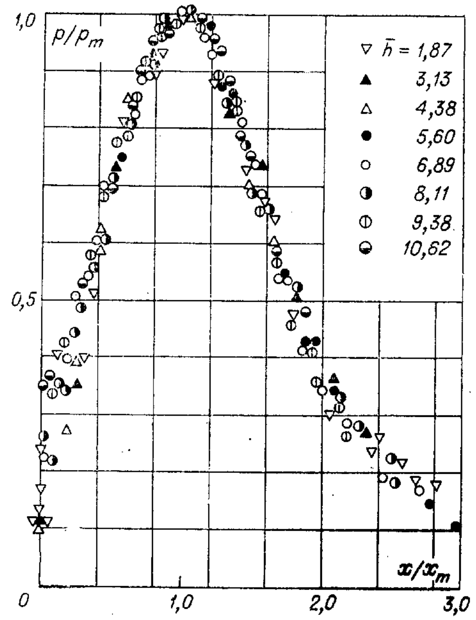

Fig. 6

The generalized pressure profile along the flow line is shown in Fig. 6 (for a nozzle with a ratio of the exit and critical cross-section diameters $\xi = 2$, $Re_* = 2 \cdot 10^3$). It has been established experimentally that as the degree of expansion of the nozzle increases the height of the load profile, constructed at the coordinates x/x_m and p/p_m, increases and, in addition, in the range $\xi = 1.3$-3.25 for the relative coordinate $x/x_m = 2$ this increase does not exceed 10% of the maximum value of p/p_m and the data shown in Fig. 6 can be used for estimating the load distribution along the flow line on the surface.

Thus, in order to determine the magnitudes of the local force loads along the flow line in the region of interaction between a supersonic stream with a large degree of nonsimilarity and a contiguous flat surface parallel to its axis, it is necessary:

1) to determine with the help of the function (2) the coordinate of the load maximum;

2) to determine with the help of the function (3) the magnitude of the maximum pressure on the surface;

3) to construct a pressure profile with the help of the generalized pressure profile along the flow line for a nozzle with a known degree of expansion.

In conclusion we note that in the present work we did not investigate the effect of nonequilibrium in the internal degrees of freedom and condensation on the nature of the distribution of loads and their magnitudes. Such effects were avoided with the appropriate choice of starting parameters.

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LARGE-SCALE MOTION HYPOTHESIS FOR A GAS—FLUID FLOW

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The experimental information concerning the local characteristics of gas—fluid flow accumulated in recent years provides a stimulus for the development of semiempirical methods for studying such flows.

In the work available until now, a two-phase mixture is often considered as a locally homogeneous fluid, to which the assumptions concerning the hydrodynamics of single-phase flows are applied [1, 2]. At the same time, large-scale fluctuations in the hydrodynamic quantities, velocity, pressure, and gas content, are no longer considered.

The role of large-scale fluctuations in the gas—fluid flow is demonstrated in [3] via an analysis of the balance of turbulent energy, according to which there is a transformation of energy in the fluctuating (macroscopically fluctuating) motion into the energy of averaged motion in a two-phase flow. The presence of large-scale fluctuations must be taken into account in the starting equations for the conservation of mass, momentum, and energy in two-phase flows.

Many Soviet and foreign researchers have been concerned with the construction of a system of differential equations that describes the motion of multiphase systems. An analysis of the best-known work is given in the reviews [4, 5].

One of the basic questions is the choice of scales for averaging the integral conservation equations. Most researchers consider the two-phase mixture as an incompressible fluid with dispersed solid particles. It is assumed beforehand that both components are present in the volume of the mixture that is being averaged and, in addition, the volume concentration does not depend on the size of the averaging volume down to infinitely small volumes.

As a result, correlations that contain concentration fluctuations appear in the averaged equations.

This approach can be used for mixtures in which the dimensions of the occlusions are significantly less than the scales over which the spatial average is performed.

In the motion of gas—fluid mixtures in the plug regime, the characteristic size of the occlusions is comparable with the scale of the flow (pipe diameter). For such a flow, it may be assumed that at any time the volume over which the averaging is performed is occupied by one of the phases.

In this case, correlations that contain concentration fluctuations vanish and averaging the equations of the conservation of mass and momentum reduces to the equations in [6]:

$$\frac{\partial}{\partial t}(\rho_i\alpha_i) - \nabla(\rho_i\alpha_i\mathbf{U}_i) = 0,$$

$$\frac{\partial}{\partial t}(\rho_i\alpha_i\mathbf{U}_i) = -(\nabla\rho_i\mathbf{U}_i)\,\alpha_i\mathbf{U}_i + \rho_i\alpha_i\mathbf{g} + \nabla(\alpha_i\mathbf{P}_i) + \nabla(\alpha_i\mathbf{T}_i).$$

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