CHARACTERISTICS OF THE ACTION OF AN UNDEREXPANDED JET ON AN ADJACENT SURFACE

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The interaction of an underexpanded jet with an adjacent surface is a most characteristic practical problem. Various aspects of this problem are dealt with in [1-8]. Nevertheless, this problem has not been completely solved and any new results are a useful addition to the available results. In this paper, we present the results of an experimental investigation, which in their turn are a logical continuation of [9].

1. As the investigation in [1-3] showed, in general, two pressure peaks are formed in the region of interaction of a jet with an adjacent surface. The first, closest to the edge of the nozzle, is due to the interaction of the compressed layer, situated between the suspended shock and the boundary of the jet, with the surface. The location of the magnitude of the first load maximum depends on the thickness of the compressed layer, the degree of expansion of the nozzle, and its position relative to the surface being examined. The location and magnitude of the second pressure maximum stems from the nonuniformity of the distribution of parameters in the flow field of the unperturbed part of a greatly underexpanded supersonic jet. For small underexpansion, the magnitude of the local loads in the region of the first maximum can greatly exceed the loads stemming from the nonuniformity of the parameter distribution in the flow field of the supersonic jet (Fig. 1, CO_2; $\xi = 1.0$; $\bar{h} = 6.88$; $Re_* = 1.6 \cdot 10^4$; $T_0 = 510°K$; 1) $n = 900$; 2) $n = 3000$). For large underexpansion ($n > 10^2$-10^3), the intensity of the first load peak does not depend on the underexpansion and is determined by the flow rate of the working body through the nozzle (or Reynolds number, defined by the parameters in the critical section of the nozzle Re_*). For a sonic nozzle, $\xi = d_a/d_* = 1.0$, situated at a distance $\bar{h} = h/r_a = 6.0$ from the surface and flow underexpansion $n > 10^4$, when the Reynolds numbers Re_* vary from $2.5 \cdot 10^3$ to $1.9 \cdot 10^4$, the nature of the pressure distribution on the surface changes from a distribution with a single maximum with small values of Re_* to a distribution with two sharp maxima for large values of Re_* (Fig. 2, CO_2; $\xi = 1.0$; $\bar{h} = 6.0$; $n = 3 \cdot 10^4$; $T_0 = 650°K$; 1) $Re_* = 2.5 \cdot 10^3$; 2) $Re_* = 6.2 \cdot 10^3$; 3) $Re_* = 8.7 \cdot 10^3$; 4) $Re_* = 1.9 \cdot 10^4$). In addition, as Re_* increases, the position of the first load maximum shifts toward the edge of the nozzle and its intensity simultaneously increases. As the degree of expansion of the nozzle ξ increases, the intensity of the first maximum decreases and the loads due to the nonuniformity of the parameter distribution in the flow field become decisive.

2. Usually, in order to determine thermal loads in the region examined, the solutions of the boundary layer equations for uniform supersonic flow past the surface are used. In addition, it is assumed that the heat flux at the point on the surface examined is determined by local parameters and does not depend on the past history of the flow. In order to find the local parameters, a model of isentropic expansion according to a given pressure profile is used. The position of a pseudocritical point (point of spreading) is assumed to coincide with the maximum pressure, while the temperature at this point equals the stagnation temperature. Thus, the existing computational scheme is quite cumbersome and contains a large number of assumptions, idealizing the real physical picture of the interaction.

At the same time, modern low-density gasdynamic installations using cryogenic evacuation permit realizing mass flow rates of the working body up to several tens of grams per second with a residual pressure $1.33 \cdot 10^{-1}$-$1.33 \cdot 10^{-2}$ Pa. This yields values of the Reynolds numbers, determined according to the parameters in the critical section, up to $Re_* \simeq 10^5$-10^6. In this connection, the most attractive, from the point of view of simplicity and reliability of the final result, are the dependences that approximate the nature and magnitude of local loads in a wide range of starting parameters. A series of results from an experimental investigation of the thermal action of the jet on an adjacent surface is presented in [1, 6-8,

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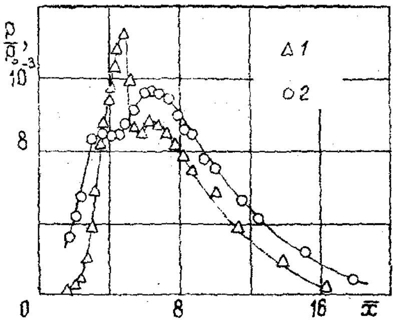

Fig. 1

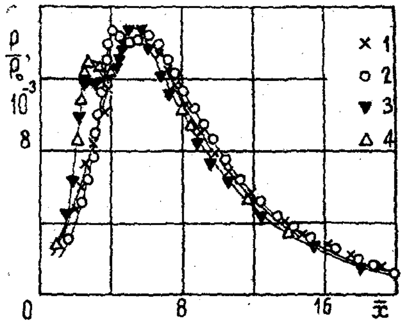

Fig. 2

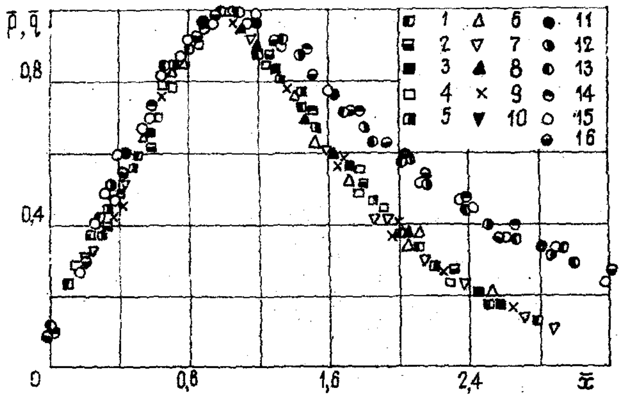

Fig. 3

10]. In [5], in order to calculate the pressure distribution along the flow line in the region of interaction, a universal profile, which generalizes the experimental data obtained with the use of air as the working body for different Mach numbers at the edge of the nozzle and with the nozzle axis displaced from the surface, is presented. The location of the maximum in this case is determined with the help of the dependences in [4]. In addition, it was established that with identical conditions at the nozzle edge and with the same position of the nozzle relative to the surface being examined, the regions of maximum pressure and heat flux coincide. This result was obtained by comparing the pressure profiles and heat fluxes on the surface, measured under the conditions of a single experiment by pressure and heat flux sensors. The use of heat indicating coatings in order to distinguish the zone with maximum heat fluxes and to compare the position of this zone with the nature of the pressure distribution, measured along the spreading line on the surface, show that the location of the pressure and heat flux maxima coincided in all cases. This result was checked for nozzles with various degrees of expansion and various displacements of the nozzles from the surface. The results in [10] do not confirm this fact.

3. Information concerning the nature of the distribution of local loads not only along the flow line, but also in the entire region of interaction of a highly underexpanded supersonic jet with an adjacent surface, is of interest. Longitudinal profiles of pressure

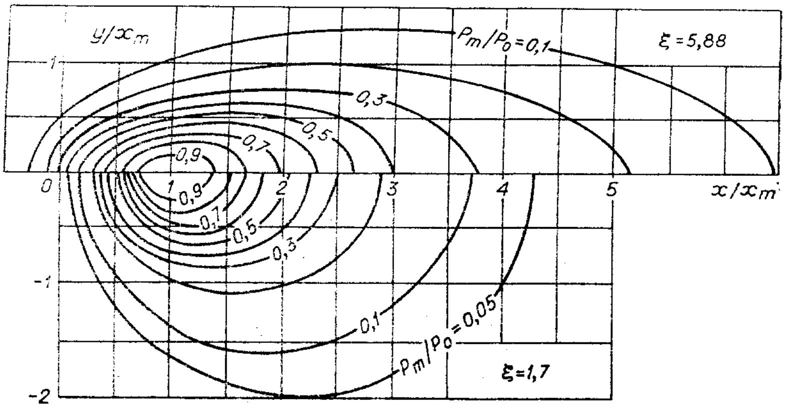

Fig. 4

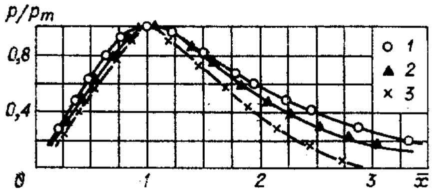

Fig. 5

and heat flux along the spreading line and in sections parallel to it are generalized for different displacements of the nozzle axis from the surface and lateral displacements, if the analysis is performed using the coordinates $\bar{p} = p/p_{max}$, $\bar{q} = q/q_{max}$, and $\bar{x} = x/x_{max}$, where p_{max} and q_{max} are the maximum values of the pressure and heat flux in the longitudinal sections examined, respectively; x_{max} is the distance from the surface of the nozzle edge to the maximum pressure and heat flux in the longitudinal section examined (Fig. 3, N_2; $\xi = 1.3$; $Re_* = 5 \cdot 10^3$; $\bar{p}$(1) $\bar{h} = 8.7$; 2) $\bar{h} = 10.4$; 3) $\bar{h} = 12.2$; 4) $\bar{h} = 14.8$; 5) $\bar{h} = 17.0$); $\bar{q}$(6) $\bar{h} = 7.4$; 7) $\bar{h} = 8.26$; 8) $\bar{h} = 9.13$; 9) $\bar{h} = 10.0$; 10) $\bar{h} = 10.8$); CO_2; $\xi = 3.05$; $\bar{h} = 1.67$; $T_0 = 630$°K; $Re_* = 1.3 \cdot 10^4$; 11) $\bar{y} = 0$; 12) $y = 0.42$; 13) $\bar{y} = 0.85$; 14) $\bar{y} = 1.27$; 15) $\bar{y} = 1.7$; 16) $\bar{y} = 2.12$). On this basis, in order to describe the local load distribution in the entire region of interaction of a greatly underexpanded supersonic jet with an adjacent surface or a nozzle with a given degree of expansion, fields with equal local load values, constructed in the same generalized coordinates for nozzles with different degrees of expansion, can be used (Fig. 4, CO_2; $\xi = 5.88$; $Re_* = 0.8 \cdot 10^5$; $T_0 = 630$°K; $\xi = 1.7$; $Re_* = 0.3 \cdot 10^5$; $T_0 = 500$°K).

4. As the investigations showed, the geometrical characteristics of the nozzle and its position and the thermophysical parameters of the working body affect the interaction of the jet with an adjacent surface. The results obtained permit a brief analysis of the effect of a number of starting parameters on the results of the interaction.

As the degree of expansion of the nozzle ξ increases, the "completeness" of the relative load profile increases (see Fig. 3). The effect of the ratio of the specific heat capacities of the working body on the relative load profile in the region of interaction shows the opposite behavior. As $\gamma = c_p/c_V$ increases, the completeness of the relative pressure profile decreases (Fig. 5, $\xi = 3.05$; $\bar{h} = 1.84$; $T_0 = 500$°K; 1) C_3H_8; $Re_* = 1.2 \cdot 10^4$; 2) air; $Re_* = 6.3 \cdot 10^3$; 3) Ar, $Re_* = 6.8 \cdot 10^3$). The change in the flow rate of the working body through the nozzle (change in Reynolds number, determined from the parameters in the critical section Re_*) leads to some deformation of the relative load profile on the adjacent surface. As Re_* increases, the relative loads at identical points on the surface decrease. The loads on the adjacent surface beneath the nozzle show the greatest change.

The results presented above permit constructing the local load field in the region of interaction of a supersonic jet with an adjacent surface for nozzles with any degree of expansion and displaced from the surface. In addition, we can recommend relations for the location and magnitudes of maximum loads [4, 5, 8, 9] and the results presented above for determining the load fields.

In conclusion, we should note that, as in [9], in this work the effect of kinetic processes (the nonequilibrium nature of the vibrational and rotational degrees of freedom, condensation) and the effect of rarefaction, in the broad sense of these concepts, were not examined. Moreover, the starting parameters were chosen in such a way that the kinetic processes indicated had no significant effect on the nature of the interaction.

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BURGERS APPROXIMATION FOR PLANE LONG-WAVELENGTH DISTURBANCES IN AEROSUSPENSIONS

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In reports devoted to the investigation of transient normal compression shocks in aerodisperse media (see [1, 2], for example), essentially only the initial stage of evolution of these shocks, the section of formation of the relaxation wave, is considered. The study of subsequent stages in the evolution of shock waves in aerosuspensions is of no less interest from the point of view of assuring industrial safety in connection with performing explosive work (mining, explosive welding, etc.). In the present report the final stage of evolution of waves in suspensions of solid and liquid particles, the stage of degeneration of a shock wave into a sound wave, is investigated by methods of nonlinear acoustics. The dissipative properties of aerosuspensions are analyzed and the structure of the shock front in this stage of evolution is examined.

We will assume that solid or liquid particles with a constant weight concentration are suspended in an inert gas in the initial stage undisturbed by the wave. Before the arrival of the wave the aerosuspension is assumed to be monodisperse, at rest in the coordinate system (x, t), and in equilibrium. In the case of liquid particles the gaseous phase contains,

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