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COLLAPSE OF SHOCK WAVES UPON THEIR INTERACTION WITH A LOCAL ENERGY SOURCE

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Numerical analysis is performed of the interaction of a shock wave with a local energy source and the wake behind it. It is shown that for specified shock-wave intensity and flow parameters there is a threshold value of the energy release starting with which the shock wave collapses.

Key words: *shock wave, energy source, wake.*

Introduction. Studies of various types of effects on gas flows aimed at controlling its characteristics are currently of great interest for high-velocity aerodynamics. One of such methods is the organization of localized regions of energy release in a gas flow. In such regions, energy supply can be implemented by means of absorption of electromagnetic energy as a result of an electric discharge of a particular nature. By creating regions of energy release in the neighborhood of flight vehicles, it is possible to perform a targeted control of their aerodynamic properties and heat exchange.

Calculations have shown that this method can be used to effectively reduce the resistance of blunt and pointed bodies [1–7]. Experimental findings have confirmed the theoretical conclusions: a considerable decrease in the resistance of both pointed bodies (cones) and blunt bodies was observed [8–11].

The interaction of shock waves with atmospheric heterogeneities of natural or artificial origin are also of interest. Primary consideration has been given to heterogeneities in the form of a lighter gas compared to the ambient gas [12, 13]. In the present paper, we consider the interaction of a shock wave with an energy source and the wake behind it.

Formulation of the Problem. In a supersonic gas flow, let there be a localized region in which energy is released in a predetermined manner. Previous studies have shown that in some cases this model can be used to simulate the real processes of energy release in an electric discharge. If the source operates in a steady-state mode, a wake of high temperature and low density is formed behind it. The flow pattern that arises in this case has been fairly well studied for sources of axisymmetric shape operating in both steady-state and pulsed-periodic modes [1–7].

The source is subjected to a plane shock wave whose front is perpendicular to the incident flow.

The problem is described by Euler equations with nonzero right side, which can be written in conservative form

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} + \frac{\partial H}{\partial z} = f,$$

Here

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ e \end{bmatrix}, \quad F = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ \rho uw \\ u(e+p) \end{bmatrix}, \quad G = \begin{bmatrix} \rho v \\ \rho vu \\ \rho v^2 + p \\ \rho vw \\ v(e+p) \end{bmatrix}, \quad H = \begin{bmatrix} \rho w \\ \rho wu \\ \rho wv \\ \rho w^2 + p \\ w(e+p) \end{bmatrix}, \quad f = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \rho q(t,x,y,z) \end{bmatrix},$$

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t is time, x, y, and z are Cartesian coordinates, ρ is the density, p is the pressure, u, v, and w are the velocity components, $e = p/(\gamma - 1) + \rho(u^2 + v^2 + w^2)/2$ is the total energy of a unit volume of the gas, γ is the isentropic exponent, and $q(t, x, y, z)$ is the distribution of the rate of energy supply to a unit volume.

The dimensional quantities are made nondimensional with respect to their values at infinity.

Numerical Solution Technique. The finite volume method was used to construct a system of finite-difference equations for the conservative system of differential equations. The flows through the boundaries of the volume cells in the x direction are calculated using the approximate solution of the Riemann problem (see [14, 15]):

$$\Phi_{m+1/2} = \frac{F_m^k + F_{m+1}^k}{2} + |A|_{m+1/2}^k \frac{U_m^k - U_{m+1}^k}{2}, \qquad |A| = \Omega_R[|\lambda_p|\delta_{pl}]\Omega_L.$$

Here Φ is the flow; the matrices Ω_R and Ω_L are obtained by diagonalization of the matrix $\partial F/\partial U$:

$$\frac{\partial F}{\partial U} = \Omega_R \Lambda \Omega_L, \qquad \Lambda = \mathrm{diag}\,[u - c, u, u, u, u + c]$$

(c is the sound velocity at a particular point). In the other axial directions, the flows are calculated similarly using the corresponding change of matrices. The boundary conditions at infinity are satisfied from the condition of vanishing of the normal derivative of the solution. The time step for the explicit difference scheme obtained in such a manner was chosen using the Courant–Friedrichs–Levi stability condition:

$$\max|C_x| + \max|C_y| + \max|C_z| \leqslant 1.$$

Here C_x, C_y, and C_z are the Courant numbers along the x, y, and z axes, which are expressed in terms of the maximum eigenvalues of the matrices $\partial F/\partial U$, $\partial G/\partial U$, and $\partial H/\partial U$, respectively.

For steady-state problems, a relaxation method with a comparison of successive (in time) solutions in a uniform norm was employed.

The calculations were performed on a $516 \times 201 \times 101$ spatial grid. Memory for all components of the solution vector U was allocated in a unified array, and data for the physical components of the vector were stored sequentially at each point of space. This allowed us to use functions for vector operations at each spatial unit.

Calculations Results. Below we give calculation results for a local energy source with a Gaussian distribution of the heating rate in space:

$$q(t, x, y, z) = Q_0 \exp(-x^2/a_x^2 - y^2/a_y^2 - z^2/a_z^2).$$

The axes of the corresponding ellipsoid are $a_x = 0.5$ and $a_y = a_z = 0.3$. The source is in a gas flow which is homogeneous at infinity, and the streamline coincides with the x axis. The incident flow Mach number is $\mathrm{M}_\infty = 3$. The interaction of the gas flow with the locally distributed energy source produces a wake behind the source. The calculations were performed for the case of interaction of a plane shock wave which moves in the positive x direction with the source and its wake.

The Mach number at which the shock wave front moves relative to the gas flow is $\mathrm{M}_s = 2$. The dimensionless shock wave amplitude $(p_2 - p_1)/(\rho_1 c_1^2)$ is 2.5. Figure 1 shows isolines of the constant entropy function p/ρ^γ. The data are given for a source intensity $Q_0 = 20$.

The results obtained can be interpreted as follows: in the wake behind the source the gas is heated and becomes less dense. As a result, the shock attenuates in the region of the wake. In the case of a rather intense source, the shock wave collapses (becomes an acoustic wave).

Obviously, the ability of the energy source to break the shock wave depends on the incident flow Mach number, the source intensity, and the shock-wave intensity. For a fixed shock-wave Mach number M_s relative to the incident flow, we determined the critical curve on the plane (M, Q) that separates the modes of collapse and noncollapse of the shock wave. The presence of a shock was determined by analyzing the entropy variation in a gas particle according to the first law of thermodynamics:

$$T\,DS = q.$$

Here $D = \partial/\partial t + v \cdot \nabla$ is an operator of time differentiation in a gas particle.

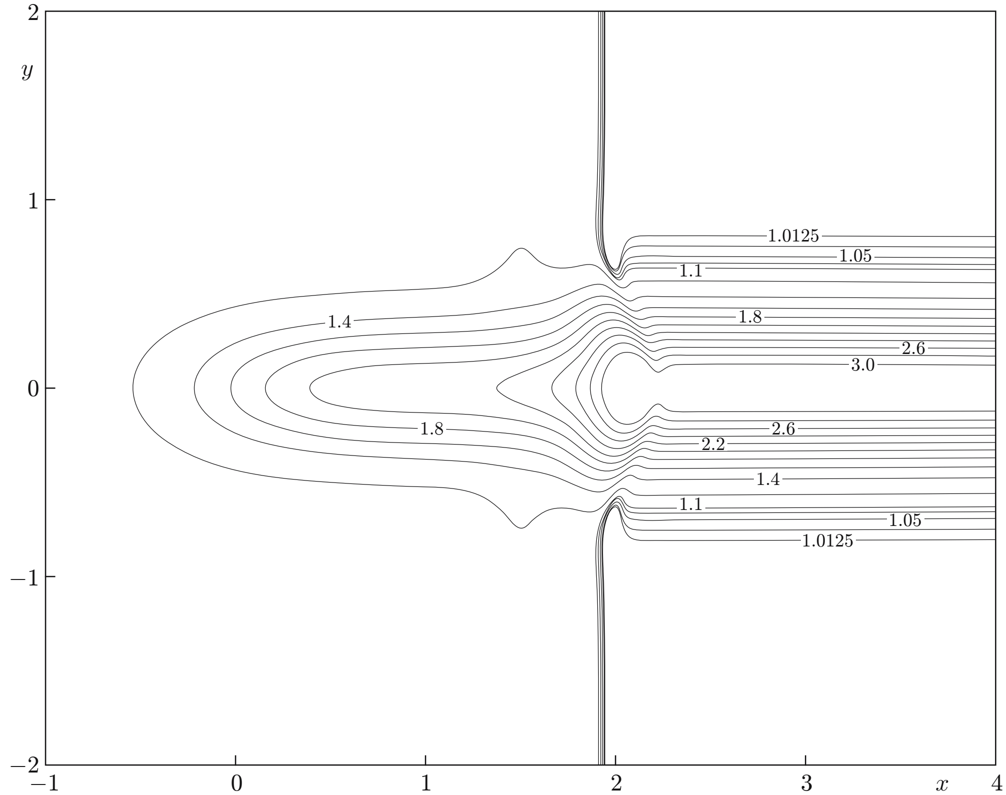

Fig. 1. Entropy isolines for $Q_0 = 20$, $M_\infty = 3$, and $t = 2.5$.

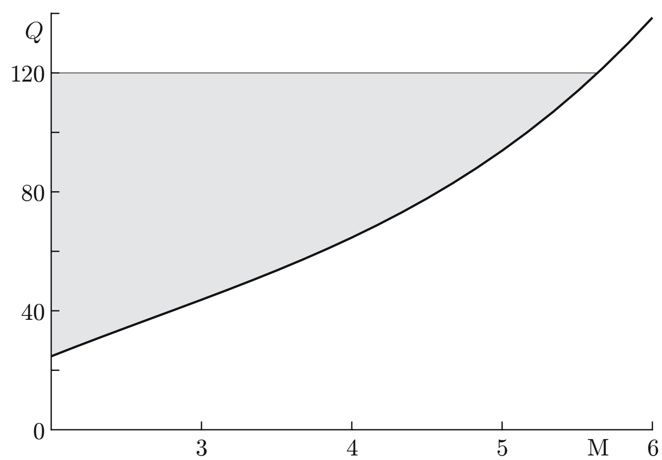

Fig. 2. Region of collapse of the shock wave.

Integration of this equation taking into account the particle trajectory leads to an entropy in the in this particle with allowance for the energy source. If the particle passes through the shock, an additional entropy increment arises. The absence of this additional increment suggests that the shock wave collapses, i.e., becomes an acoustic wave. This procedure was implemented as a software process, which made it possible to analyze a large body of data without their full visualization.

A series of calculations was conducted for various incident flow Mach numbers and source intensities. Processing of the results of these calculations yielded the critical curve shown in Fig. 2, above which there is a region of breaking of the shock wave by an energy source.

Conclusions. The interaction of a shock wave with an energy source and the wake behind it was studied for various characteristics of the flow and the source using Euler equations. It was shown that the presence of the source leads to a considerable attenuation of the shock wave, and if the energy supply rate exceeds the threshold value, the shock wave collapses.

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