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PLANE SHOCK WAVE CUMULATION IN A TUBE WITH A THIN WALL LOW-DENSITY GAS LAYER

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A new effect of focusing of a shock wave disturbed by a thin low-density gas layer localized near the side wall of the cylindrical tube, followed by the wave reflected from the flat tube end, is analyzed numerically.

A thin extended low-density gas layer in front of a shock wave normal to a shock front can give rise to a large-scale, self-similarly growing disturbance of the front - a "precursor" shaped as a wedge or a funnel [1]. A rarefied gas layer near a solid wall is generated naturally, for example, in a shock tube when its walls are acted upon by thermal radiation of a strong shock wave front [2, 3] or can be initiated artificially: in electric pulse heating of the surface [1, 4], by a laser beam [5] (in this case, the presence of a surface is optional), or by some other means.

The formed specific cumulative geometry of the wall layer-disturbed shock front, concave in its propagation direction, affords necessary conditions for the effect of locally enhancing the shock wave, followed by its reflection from the flat end wall of the tube (or by symmetric collision of the two waves). Note that such an effect fundamentally differs from the process of focusing a plane shock wave reflected from a curvilinear tube end, analyzed in [6].

Let us present some results of numerical simulation of this effect within the framework of the Euler equations with the use of an antidiffusion scheme of the type cited in [7]. Let a stationary plane shock wave at the initial time $t = 0$ with Mach number M_0, propagating in a cylindrical tube of radius R_0 and filled with an ideal gas having adiabatic index γ, start interacting with a rarefied cylindrical gas layer of thickness $\delta << R_0$ and length $L_0 >> \delta$ localized near the wall, which ends near the flat tube end (or the symmetry plane). The process of the self-consistent formation of such a layer in the adopted model formulation is not considered. The layer density $\rho_l = \omega\rho_0$, $\omega < 1$ (ρ_0 is the bulk gas density) is assumed to be constant and the pressure p_0 over the entire gas mass in front of the shock wave is assumed to be equalized, i.e., the layer gas proves to be heated ω^{-1} times compared to the bulk one.

The ratio of the maximum pressure at the end center to the analytically determined (see, e.g., [8]) pressure behind the front of the stationary plane shock wave reflected from the tube end with no disturbing layer $\eta_l = p_m/p_r$ will be taken as a controlling parameter that characterizes the cumulation efficiency when the layer-disturbed shock wave is reflected from the tube end.

Let us consider the dynamics of the cumulation process of a shock wave having an extremely large intensity ($M_0 >> 1$). Calculation is made for $\omega = 0.1$ and $\gamma = 1.4$. In the figures below, all quantities are reduced to dimensionless ones, without using additional notation: cylindrical coordinates r, z are normalized to R_0 (the coordinate origin coincides with the end center); the time, to the quantity R_0/U_0, where U_0 is the speed of a piston generating a shock wave; the pressure, to the quantity $\rho_0 U_0^2$.

The isobar field in Fig. 1 exhibits the shock front configuration and the characteristic behavior of flow behind the front at the first moment of time after the precursor top has been reflected from the tube end. Starting with this moment, the cavity, shaped as a truncated cone and filled with a stagnant buffer gas, starts to collapse.

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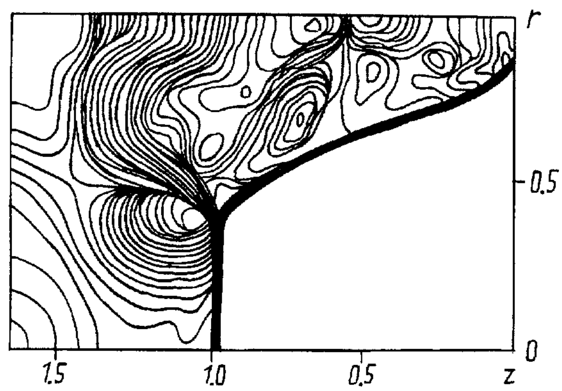

Fig. 1. Pressure isolines at the time $t \approx 1.8$ that the shock wave starts reflecting from the end wall.

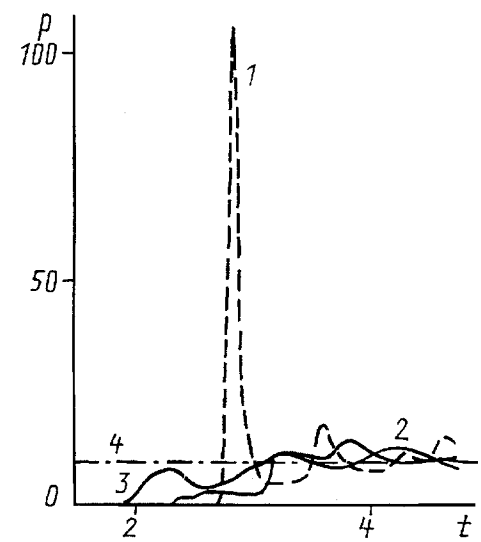

Fig. 2. Time-dependent pressure on the end wall: 1) $r = 0$; 2) 0.5; 3) 1; 4) pressure behind the front of the reflected stationary plane shock wave.

At fixed values of the parameters M_0, ω, and γ, the collapse efficiency is substantially determined by the ratio L_0/R_0, stipulating the relative precursor length l_p/R_0 at the time its top must impinge on the end wall of the tube. As the ratio L_0/R_0 increases, there occurs a flow transition from the regime with a self-similarly growing precursor to that with a stationary funnel-shaped precursor occupying the entire tube cross section. Optimal gas compression near the end center will be attained when the enhanced cylindrical shock wave propagating over the end from the periphery to the cylinder axis and the "remains" of the plane shock wave propagating along the axis to the end simultaneously come together at this center. The roughly optimized relative length of the disturbing layer in this case was $L_0/R_0 \approx 3.5$. As is seen from Fig. 1, for this value of L_0/R_0 the precursor at the time it impinges on the end is not yet stationary and does not approach the maximum possible size.

Time-dependent pressures on the end wall at different distances from the center are plotted in Fig. 2. Here, the constant pressure p_r when the disturbing wall layer is absent is also plotted. It is seen that the end center pressure is enhanced by an order of magnitude compared to p_r at the time $t \approx 2.8$ (note that a corresponding fivefold increase of the center density, as compared to the density ρ_r behind the reflected plane shock wave front, is attained at this time).

Thus, on a qualitative level within the framework of the adopted simplest computational model the cumulation effect of the thin rarefied gas layer-disturbed shock wave reflected from the tube end may be considered to be found.

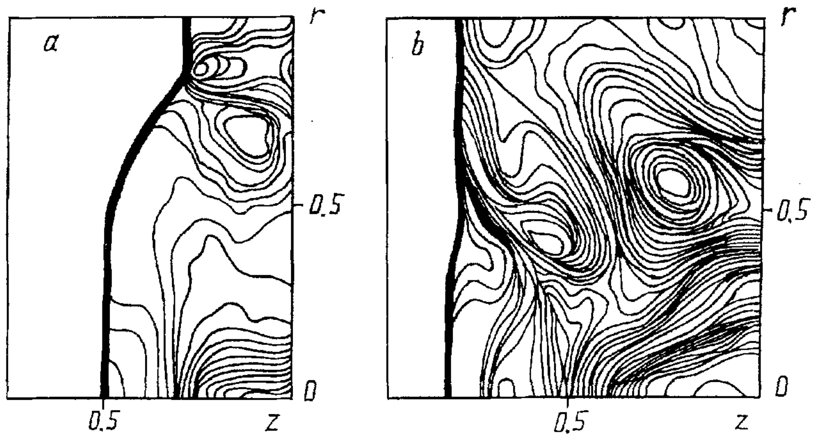

Fig. 3. Pressure field at t ≈ 3.6 (a) and t ≈ 4.7 (b).

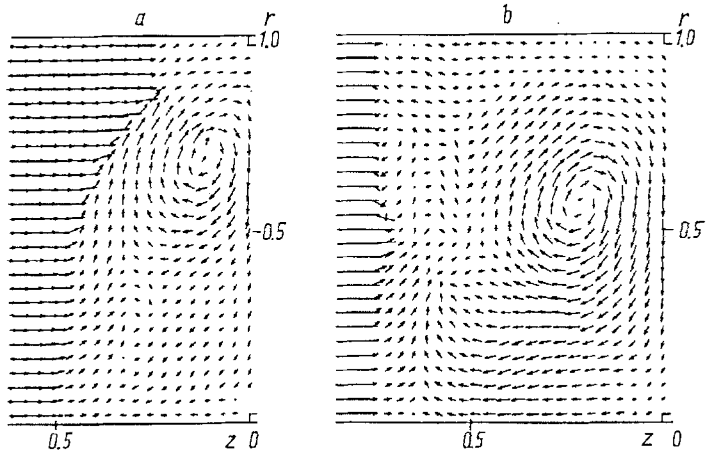

Fig. 4. Velocity field at t ≈ 3.6 (a) and t ≈ 4.7 (b).

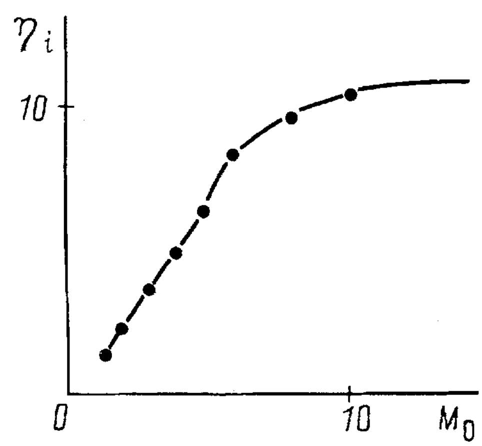

Fig. 5. Gain coefficient η_l as a function of Mach number for an incident shock wave.

As would be expected, the effect is local in nature: the pressure rapidly falls with time and distance from the end center. Since in the calculations relatively rough difference schemes with a typical spatial resolution of 30×100 nodes are used, the obtained quantitative value of η_l should be considered as an estimate bound from below that may be further refined. However, it should be borne in mind that real cumulative flows of this type may prove to be unstable, thus resulting in a maximum pressure reduction. A sufficiently rigorous simulation of such effects is, apparently, possible only within the framework of three-dimensional geometry.

After the shock wave has been reflected from the end, the flow remains disturbed for a long time over the entire tube cross section and includes large-scale eddy formations (see Figs. 3, 4).

The relation $\eta_l(M_0)$ with the values of the parameters ω, γ and L_0/R_0 fixed, in contrast to the previous case, is plotted in Fig. 5. The qualitative picture of the phenomenon for varying incident shock wave Mach number does not change substantially compared to the previously described one, but the relative length L_0/R_0 of the disturbed flow already does not provide maximum compression at the end center.

Of interest is the experimental check of the predetermined cumulation effect of plane shock waves.

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