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CUMULATIVE EFFECT OF A SHOCK REFLECTED FROM A SPHERICAL CONCAVE WALL

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The cumulative effect originating during shock reflection from a cylindrical concave wall at the end of a rectangular shock-tube channel is described in [1]. The intensity of the reflected wave (the Mach number M) hence grew ~ 1.5-fold as compared with the case of wave reflection from a flat wall.

Experiments were performed in a shock tube whose construction is similar to that described in [2]. The shock-tube chamber and channel were fabricated from ordinary steel tubing with a 208 mm inner diameter. The measuring section, a steel tube with 120 mm inner diameter, was placed at the end of the channel. The forward part of this tube with sharp edges was set deep in the channel with such a design that the wave running between the channel walls and the measuring section would not influence the flow in the latter during the experiment. Acetate cellulose films 0.2 mm thick in two layers were used as the working diaphragm. Air was on both sides of the diaphragm; at atmospheric pressure in the channel and at a 2.5 gage atm pressure in the chamber; the shock-wave Mach number was 1.27 ± 0.01.

Presented in Fig. 1 is a diagram of the measuring section apparatus, where the experiment was performed. The ends of the measuring section were compactly plugged by the organic glass entrance plug 1. The plug end face had a hollow in the form of a spherical cup. A ~ 1-mm-wide slit 2 was sawed through the body of the plug. The plane of the slit coincided with the axis of the measuring-section tube. Two ~ 10-mm-wide windows 3 in which glass with flat surfaces was set were cut out of the measuring section wall. A 0.4-0.5-mm-wide regulatable slit was mounted on the outer surface of one of the windows. During assembly of the measuring section and its apparatus in the shock tube, the shock-tube axis, the slit in the plug, the windows in the walls of the measuring unit, the regulatable slit, and the optical axis of the photorecording system were all in one plane.

The process of shock reflection was recorded by using an IAB-451 shadowgraph and a coupled SFR camera in the photo-chronograph mode. An IFK-120 pulsed light source was used for bias lighting. Start-up of the light source was accomplished by a pulse from a piezosensor.

The shock-tube diaphragm was broken by using the electrical explosion of a wire. This permitted synchronization of shock tube and SFR camera operation.

The magnitude of the concavity of the wall from which the shock is reflected is characterized by the dimensionless parameter h/R, where h is the height and R the radius of a spherical segment (see Fig. 1). A series of experiments was performed in which h/R varied between 0.1 and 0.9.

The geometry of the experiment excludes the possibility of obtaining shadow photographs of individual instants of the flow picture, as had been done in [1]; however, the similarity of the x vs t diagram in any case permits a qualitative representation of the flow picture (Fig. 2) in the experiments described below. In the case $h/R \geq 0.5$, the shock being reflected from the bottom of the segment acquires the spherical shape r_1 (Fig. 2a). The cumulative effect originates upon collapse of the cylindrical transverse wave w on the tube axis, and the transverse wave originates under the effect of a stream of substance sliding along the segment walls toward the center. This stream appears during reflection of an incident wave on the sloping walls of the spherical

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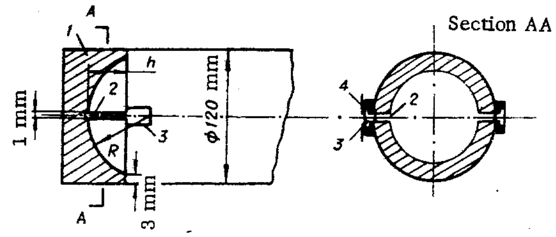

Fig. 1

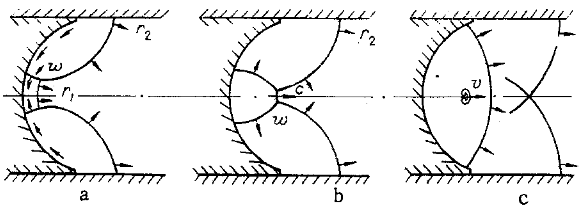

Fig. 2

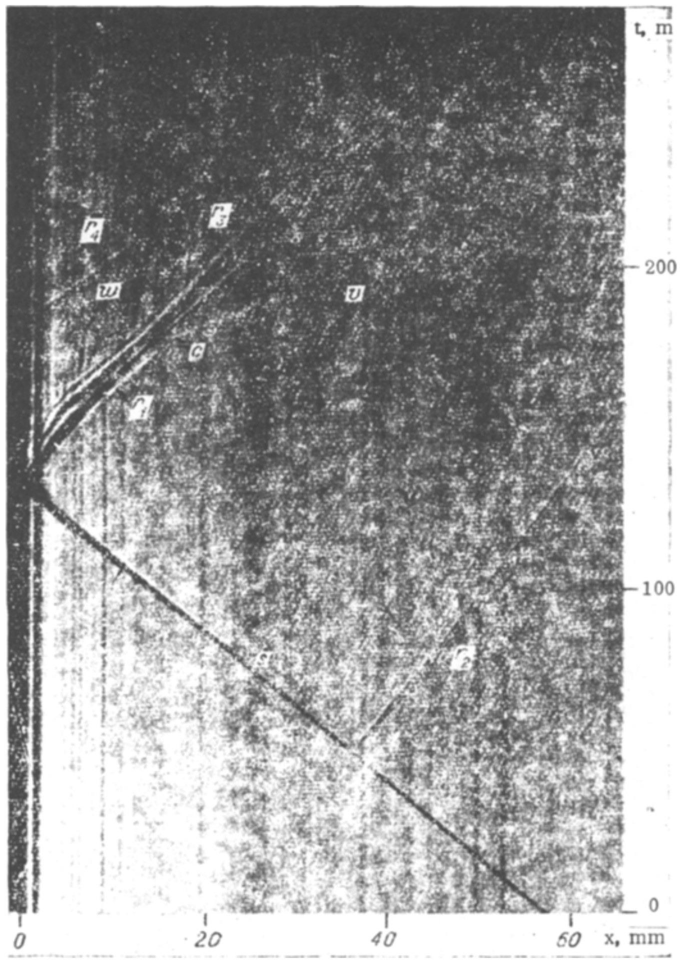

Fig. 3

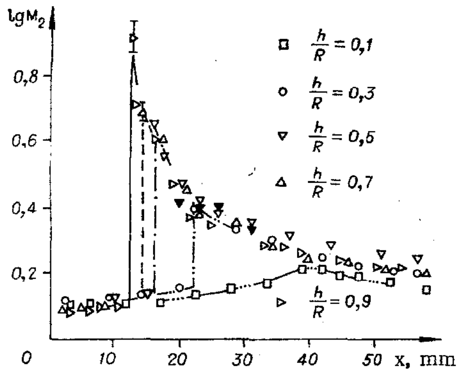

Fig. 4

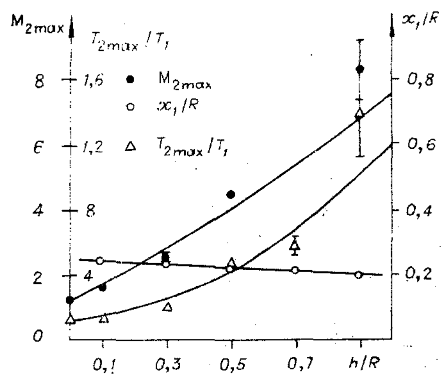

Fig. 5

segment. Collapse of the transverse wave w results in a jump in the reflected-wave velocity c (Fig. 2b) in the axial direction. Then the wave diverges and its intensity drops rapidly.

A small portion of the gas heated and accelerated to high velocity (1-2 km/sec) by the shock c at the time of its formation is expanded and forms the vortex ring v (Fig. 2c) whose velocity then dies out rapidly. The motion trajectories of these waves and the vortex can be traced on the x vs t diagram of one of the experiments ($h/R = 0.5$) presented in Fig. 3, where s is the front of the incident wave, r_1 is the converging spherical wave reflected from the bottom of the segment, r_2 is the trajectory of the front of the wave branch reflected from the forward edge of the segment, w is the wake of the collapse of the transverse wave, and v is the motion trajectory of the vortex ring.

The secondary effect of the slit in the body of the segment is the origination of the wave r_3 moving along the slit and lagging the waves r_1 and c; the transverse wave collapses into the shape of a cone with apex turned toward the reflected wave. The wave r_4 originates during collapse of the transverse wave w on the bottom of the segment.

In the cases $h/R \leq 0.5$ certain deviations are observed from the flow picture described above. For $h/R \leq 0.3$ no vortex is formed, but in the case $h/R = 0.1$ the break in the reflected wave trajectory on the x vs t diagram is replaced by a smooth bend. According to the time sweeps (the x vs t diagrams) of the flows along the axis of the shock-tube channel, the velocity and certain other parameters of the state behind the reflected-wave front can be determined. The velocities of the incident and reflected waves, as well as the velocity of vortex motion, were measured by means of the slope of the trajectories on negatives of the x vs t diagrams by using a BMI-1 microscope. The reflected-wave Mach number M_2 and temperature T_2 behind the reflected-wave front were computed under the assumption of a constant value $\gamma = 1.4$ and an initial speed of sound of 344 m/sec in the air in front of the incident-wave front.

Presented in Fig. 4 is the dependence of M_2 on the path x traversed by the reflected wave r for different values of h/R. Let x be measured from the bottom of the segment. The blackened points are obtained from measurements of the vortex velocity. These measurements actually determine the mass flow rate of the material behind the shock front and yield an additional confirmation of the shock velocity by direct measurements. The errors here and henceforth are presented with a 50% probability. In the case $h/R \geq 0.3$ the wave intensity initially grows slightly and then increases by a jump; hence, the maximum value of M_2 is reached. Right after this, M_2 starts to diminish. These singularities appear more rarely, the greater the ratio h/R. In the case $h/R = 0.1$, a rise in the reflected-wave intensity is observed, but without a jump.

The M_{2max} increases with the increase in h/R (Fig. 5), and the distance x at which the jump in reflected-wave velocity occurs diminishes simultaneously, but the relative magnitude of x_1/R depends weakly on h/R. Results of computing the greatest achievable values of the temperature T_{2max} are presented in Fig. 5 as a function of h/R. For a shock with $M_1 = 1.27$ in air reflected from a flat rigid wall, the computation yields the value 400°K for the temperature T_2. At the same time, it follows from the data in Fig. 5 that a temperature of ~3500°K is achieved behind the reflected-wave front in the case $h/R = 0.9$. At such temperatures a noticeable change in the value of γ should occur; however, the characteristic distances at which maximum values of the wave velocity are realized are very small, and the characteristic times are correspondingly small. For the case $h/R = 0.9$, the reflected-wave Mach number drops from ~ 8 to 4 in distances on the order of 1-2 mm during a time on the order of 0.5-1 μsec. Equilibrium is not established successfully at ≤ 3500°K temperatures during such brief times, and the change in γ can be neglected.

The presence of the slit in the body of the segment somehow perturbs the flow; however, the perturbations on the shock front damp out approximately 10-fold within the distances $\sim 3\lambda$ (λ is the perturbation wavelength) [3]. In our case λ is on the order of the slit width. The minimum distance within which a velocity jump occurs in the experiments described (for $h/R = 0.9$) is $x_1 = 12$ mm, which is much greater than the slit width of ~ 1 mm. The presence of the slit, if it does exert an influence, will exert an influence which is more often toward the diminution in the effect of cumulation.

In conclusion, let us note that more special forms of the hollow in the end face of the plug at the end of the shock-tube channel can result in a still greater effect. In particular, the shape of a segment surface in which collapse of the transverse wave would be realized in the form of a cylinder or of a cone with apex turned toward the bottom of the segment can result in magnification of the effect.

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STREAM MODELS APPROXIMATING THE PROPERTIES OF SUPERSONIC JET FLOWS

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§1. A free supersonic off-design jet is often the incoming stream or background for more complex phenomena and processes (Fig. 1, where the dashes are contact discontinuities and the solid lines are shocks). Hence, the simplicity of the analytical description of such jets is an important condition for the successful solution of problems of a higher degree of difficulty than the jet itself. Let us examine the following most simple model of a free jet: a one-dimensional supersonic stream moves in a channel with permeable walls. The escape velocity through the holes in the walls equals the local speed of sound. By increasing the area of the holes, we obtain a one-dimensional stream in the limit in which the velocity along the normal to the cylindrical surface equals the speed of sound. If the escape occurs into a medium with counterpressure, then a shock will appear at some intermediate secton of the channel. Its position is easily determined and corresponds practically exactly with the position of a central shock in an underexpanded jet. A simple improvement of this rough model permits obtaining good qualitative results relative to all the fundamental supersonic jet parameters in the free expansion domain (domain I in Fig. 1). The flow in a channel with variable cross-sectional area and with permeable walls is considered as the approximating stream. In the limit, the role of the permeable wall is played by one of the characteristic surfaces, which converge with the nozzle edge whose shape is determined to fourth-order accuracy relative to the angle of stream divergence.

Let us form the mathematically presented considerations by using the following notation: x, y are the coordinates in the plane of the axial stream section; u, v are velocity projections on the x, y axes; w is the absolute value of the velocity; ϑ is the slope of the velocity vector to the axis of symmetry; M is the Mach number; α is the Mach angle ($\sin\alpha = 1/M$); k is the ratio of the specific heats; p is the pressure; ρ is the density; h is the static heat content; h_m is the total heat content; S is the entropy; ψ is the stream function; and the equation of state is assumed given in the form h(p, S). The parameters on the jet boundary are denoted by the subscript H and on the nozzle exit by a. We consider all the quantities dimensionless: the coordinates are

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