INFLUENCE OF THE PHYSICOCHEMICAL PROPERTIES OF GASES ON SHOCK INTERACTION WITH CONVEX CYLINDRICAL SURFACES

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The influence of physicochemical processes in gases on the formation of perturbations in the flow behind a shock front during interaction with a cylindrical obstacle is examined.

At this time more and more attention is paid to questions of shock stability investigation. A number of anomalous phenomena have been detected, and they have been classified for monatomic gases in [1]. The majority of such phenomena is observed if and only if physicochemical transformations occur in a gas because of strong shocks [2]. However, under the same conditions the influence of perturbations on the shock, due to inhomogeneities on the surface along which it moves, is magnified. A cylindrical segment can be considered as an example of an inhomogeneity on a surface.

Shock interaction with cylindrical segments was investigated in the shock tube of square section described in [3]. The Mach numbers varied in the range 1.5-6.0, and the initial pressures varied between 10 and 30 torr. Cylinder segments with 123 mm radii, which were distinguished by the angles α_0 connecting the plane to the cylinder surface, were used as models. The angles varied between 71 and 4°. For $\alpha_0 \sim 4°$ a linear approximation in the analytic solution of such a problem can be used.

The wave configurations for two successive times corresponding to the location of the incident shock (being propagated from left to right) on the leading (a) and trailing (b) slopes of the segment are represented in Fig. 1. If the initial angle connecting the cylindrical surface to the plane is greater than the critical, then regular wave reflection occurs first, and then at the critical angle of incidence the type of reflection is replaced by Mach type, i.e., a triple point is formed that starts to move over the trajectory OA (Fig. 1a). As the Mach wave propagates over a curved surface, it is diffracted. Separation of the flow along a stall line occurs as this process develops. The subsequent course of the process results in the formation of a stationary coflow around the surface behind the shock moving at the Mach number M_1. At the frontal point for a semicylinder, a reflected wave is propagated at the first instant of collision just as in normal reflection from a plane wall, its motion is then retarded because of flow spreading along the cylinder surface, and finally, the wave occupies a position corresponding to the stationary position in the flow around a cylinder. A new triple point occurs in the passing wave at the time of its meeting with the cylinder because of reflection of the diffracted wave from the horizontal plane. Therefore, because of shock interaction with the segment, it is deformed, and breaks occur (at the sites of the triple points) from which the reflected shocks and the contact surfaces start.

Sequential shadowgraphs and interferograms of the interaction domain were obtained during the experiments. Argon, nitrogen, and carbon dioxide gases were used, whereupon the different degrees of physicochemical transformation in the gas behind the shock could be modeled. No excitation of the nitrogen molecule vibrations and dissociation occurs for the velocity and time range during which the shocks interact with the segment, and the gas behaves as an ideal gas with the adiabatic index $\gamma = 1.4$. Molecule vibrations are excited in the carbon dioxide gas, but no dissociation occurs, and if the representation about the effective adiabatic index is used, then the hot-gas parameters behind the shock correspond to $\gamma = 1.18$. For argon $\gamma = 1.67$.

The influence of physicochemical processes on shock interaction can be described as follows. Endothermal physicochemical transformations that occur in the gas behind the shock

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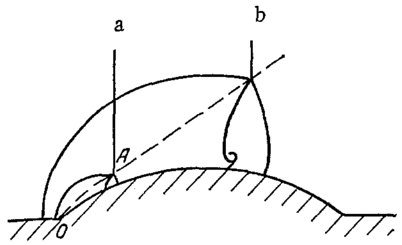

Fig. 1

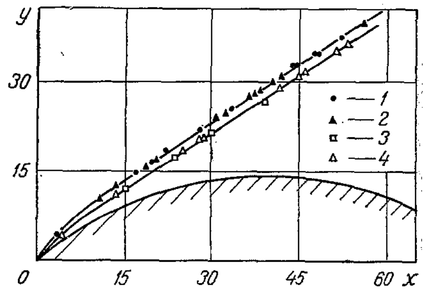

Fig. 2

Fig. 1. Wave configuration during shock interaction in nitrogen with a cylindrical surface: a) Mach reflection, $M_0 = 2.5$, $t = 2.9 \cdot 10^{-6}$ sec; b) shock diffraction, $M_0 = 2.5$, $t = 104 \cdot 10^{-6}$ sec; t is the time of shock motion from the nose of the obstacle to the position under consideration; inital pressure 10 torr.

Fig. 2. Triple point motion trajectories in Mach configurations during shock reflection from a cylindrical segment with the connection angle $\alpha_0 = 34°$; 1) M_0 = 4.2-4.7; 2) 2.3-2.5; 3) 2.7-3.0; 4) 4.6-5.0 (1, 2 nitrogen; 3, 4 carbon dioxide gas); initial pressure 10 torr. x, y, mm.

front at high temperatures will result in a reduction in the adiabatic index and an increase in the density ratio on the shock, whereupon the coflow Mach number increases. Thus, for instance, as the shock moves in carbon dioxide gas in the shock tube with the incident shock Mach number increasing to 10, the coflow Mach number reaches the value 1.8 if the observation times are short and the physicochemical processes did not occur successfully; the coflow Mach number becomes 3 for the same incident-wave Mach number at times at adequate for the gas to go into a state of total equilibrium [3]. At the same time, as is known, physicochemical processes exert slight influence on the pressure behind the incident-shock front because the temperature abruptly drops simultaneously with the rise in density.

Many shock interaction processes can be considered on the basis of the theory of decay of an arbitrary discontinuity, the shock polars being constructed in pressure—velocity coordinates, while conditions on equality of the pressures and the normal velocities are given on the contact surfaces. Since the physicochemical processes influence the pressure slightly, but alter the gas velocity substantially, then the influence of the physicochemical transformations on the shock configuration obtained during their interaction is also significant.

The following elements can be extracted from the flow pattern: a normally reflected wave, the oblique part of the reflected shock, a three-wave configuration, contact discontinuity lines, and stall lines. The influence of the physicochemical processes on the individual elements can be traced. For the normally reflected wave, the coflow velocity increase evidently results in a diminution of the reflected wave velocity in the initial stage and a diminution in the standoff distance from the body in the stationary stage. The wave seems to be pressed to the body by the coflow [4]. The diminution in the adiabatic index affects the wave configuration analogously to the increase in the incident-wave Mach number. The oblique shock in the regular and Mach reflection stages is also squeezed to the body. Indeed, the angle of gas flow deflection for an oblique shock depends on the ratio between the gas velocities on both sides. A result of computing the dependence of the angle of flow deflection on the angle of its influx into the shock is presented in [3] for carbon dioxide for an incident shock of U_0 = 1.9 km/sec. The computation was performed with and without the physicochemical transformations taken into account. For the very same 10° angle of flow deflection, the angle between the wave and the flow equals 30° in one case, and 60° in the other. These shock properties also specify an increase in the domain of existence of regular reflection as the gas adiabatic index diminishes.

The influence of the physicochemical transformations on wave disposition in a triple configuration is especially substantial. A dependence of the slope of the reflected wave ω_2 on the slope of the incident wave ω_1 (the angles are determined with respect to the triple point trajectory) for carbon dioxide gas U_0 = 1.9 km/sec calculated for different values of the effective adiabatic index is presented in [3]. It turns out that the angles ω_2 change not only their magnitude by 30-40° but also their sign, resulting in an abrupt change in the configuration as a whole. Thus, the influence of the physicochemical transformations results

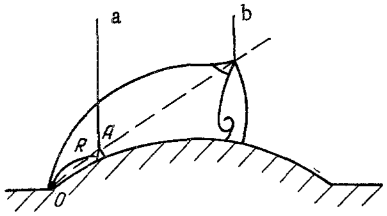

Fig. 3

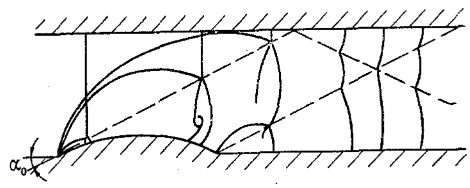

Fig. 4

Fig. 3. Diagram of shock interaction with a cylindrical surface in carbon dioxide gas: a) double Mach reflection; R is the second triple point; $M_0 = 2.8$; $t = 29 \cdot 10^{-6}$ sec; b) shock diffraction; initial pressure 10 torr; $M_0 = 2.8$, $t = 115 \cdot 10^{-6}$ sec.

Fig. 4. Diagram of shock perturbation formation during shock interaction with a rough surface. Dashed lines are triple point motion trajectories.

in the appearance of a new Mach configuration, the so-called double Mach configuration, for reflection from a wedge. This configuration is also observed in reflection from a concave surface [5, 6].

As the present experiments showed, during shock interaction with a cylindrical surface the changes in the flow patterns because of physicochemical transformations are analogous to those observed on a plane wedge. The bow wave and oblique part of the reflected wave are squeezed closer to the body, the regular reflection stage is stretched out, and a double Mach configuration occurs instead of the simple Mach configuration, i.e., an additional perturbation in the reflected wave appears. The point of shockwave intersection starts to move over the curvilinear trajectory on the cylinder surface with the origination of Mach reflection. The triple point trajectory in the gas at which the physicochemical transformations occurred is located closer to the body than in a gas with unperturbed degrees of freedom. An illustration of triple point trajectories in nitrogen and carbon dioxide gas is given in Fig. 2.

The contact surfaces occurring because of Mach reflection are turned into large-scale vortices. Vortices reach large dimensions in a gas with excitation of the internal degrees of freedom, and start to be removed from the surface of the body. Figure 1 is constructed from photographs of shock interaction with a cylindrical segment in nitrogen. Diagrams constructed from photographs of tests made in carbon dioxide are presented in Fig. 3. All the process features noted are visible upon comparing these figures: the shock is squeezed to the body, a double Mach configuration occurs in CO_2, the triple point motion is closer to the surface in the carbon dioxide case than for nitrogen, large size vortices form.

Wave diffraction occurs at the rear surface of the cylinder (Fig. 1b). The shape of the diffracted shock depends slightly on the degree of completion of the physicochemical processes in the gas, but the flow in the rarefaction fan that occurs during diffraction should depend noticeably on the processes occurring in the gas.

Results of experiments on the temperature drop in the centered rarefaction fan during shock diffraction by a right angle in nitrogen are presented in [3]. The temperature in the fan diminishes threefold for $M_0 = 8$ if the flow in the fan is frozen. Excitation of the vibrations results in a lower drop, and the temperature at the end of the fan drops just twofold.

The influence of the physicochemical processes should result in analogous effects for the case of an off-center fan during diffraction by a rounded surface.

On the whole, physicochemical processes occurring in the gas behind a shock will result in a noticeable change in the flow pattern, particularly in sharper breaks in the passed wave, more intensive reflected waves, and greater flow turbulence. Arbitrary curvature of the channel surface can be represented in the form of a set of several cylindrical surfaces. If the surface inhomogeneity of the channel is small, that is, the angle α_0 of connection is small (Fig. 4), then perturbations occur in the flow in the same manner as during interaction with thick cylindrical obstacles, with the sole difference that there is no regular reflection stage in this case. The triple points cause a curvature of the passing wave, and the contract surfaces that turn into vortices result in flow turbulization.

As is known from theoretical and experimental investigations [7], shocks are stable relative to perturbations occurring in the gas flow behind the shock. As the shock moves further along the tube, the plane wave shape is restored. This occurs by successive reflections of the wave from the tube walls.

Since the slope of the triple point trajectories will be smaller the greater the degree of penetration of the physicochemical processes, spoilage of the shock shape is retained longer while the intensities of the vortices being formed become greater. It should also be noted that restoration of the plane wave shape occurs in such a manner that the wave is made flatter at a certain distance from the site of wave perturbation, then its shape is distorted, simplified again, and so on. Usually the experimental section in which the observations are performed is at a certain distance from the tube inhomogeneities, which are located, say, at the site of a diaphragm component. Consequently, as the Mach number of the incident shock grows in the experimental section, the front will alternately be observed more distorted, then flatter, i.e., distortions of the front in this section of the tube can result in an apparent shock instability that noticeably distorts and complicates the flow for large Mach numbers when the degree of progress of the physicochemical processes occurring in the gas behind the shock increases.

NOTATION

M_0, shock Mach number; M_1, Mach number of the flow behind the shock; U_0, shock velocity; γ, ratio of the specific heats; α_0, slope of the tangent to the cylindrical surface at the frontal point; ω_1, ω_2, angles between the triple point trajectories and the incident and reflected shocks, respectively.

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