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Abstract

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Experimental Investigation of Mach Reflection of Shock Waves at Speeds of 1000–3000 m/sec in Carbon Dioxide, Nitrogen, and Air

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In this work, features of the irregular reflection of strong shock waves in carbon dioxide, nitrogen, and air have been discovered experimentally.

The experiments were carried out in a shock tube with a cross section of 72×72 mm^2. The length of the low-pressure chamber was 4 m, and the length of the high-pressure chamber was 1.5 m. Reflection of shock waves occurred from wedges with apex angles $\alpha_0 = 16; 24; 28; 32; 36; 45^\circ$. The process was visualized by the Schlieren method. Using a high-speed SFR-L camera, 30 successive frames of the reflection process were obtained with an exposure of 0.5 μsec and a frame-change time of 4 μsec. The FR-185 photorecorder made it possible to obtain continuous recording of the process in time (linear film speed 185 m/sec). The speed of the incident shock wave was measured from photographs and with the aid of piezoelectric sensors placed along the tube. The accuracy of determining the shock-wave speed was 5%. The experimental setup and the method for synchronizing the measuring equipment are described in work (^{1}).

Instantaneous photographs of Mach reflection of shock waves and photographic streak records of the process, obtained for Mach numbers of the incident shock wave $M_0 = 3 \div 8$ at an initial pressure of 12 mm Hg, made it possible to determine the values of the angles between all waves of the Mach configuration and the angles between the direction of motion of the triple point and the wedge surface χ.

Processing of the experimental data showed that, in the case of strong shock waves, the character of Mach reflection differs substantially from reflection of waves with Mach numbers $M_0 < 3$, studied in works (^{2}). These changes depend on the adiabatic exponent γ and are most strongly expressed in CO_2, where γ has the smallest value.

At large Mach numbers ($M_0 > 4$) the following is characteristic for all gases studied:

1) The appearance of a kink on the reflected wave, which, as the speed of the incident wave increases, becomes sharper; at the kink a new shock

wave is formed and a second triple point is produced. The occurrence of the secondary shock wave leads to additional compression of the gas by a factor of 2-3. The angle between the incident and reflected waves gradually increases and, at a certain speed of the incident wave, begins to exceed the value of the angle between the incident wave and the trajectory of motion of the triple point, i.e., the reflection angle ω_2 becomes negative (ω_2 is the angle between the reflected shock wave and the trajectory of motion of the first triple point; if the reflected wave is located above the line of motion of the triple point, then $\omega_2 > 0$). A typical picture of such a configuration is shown in Fig. 1 I. The appearance of a kink in the reflected wave in CO_2 was also noted in White' s work (^{3}). The motion of the entire configuration during reflection is self-similar to an accuracy of 3%.

2) The tangential discontinuity is sharply unstable. In the case of nitrogen, rolling-up of the tangential discontinuity into a vortex is observed (Fig. 1 II).

Measurements of the values of the angles of motion of the first triple point χ, and, consequently, of the angles of incidence ω_1 in the coordinate system associated with the first triple point,

Figure area: two columns labeled I and II, with high-speed photographs and schematic diagrams.

Fig. 1. Irregular reflection of a shock wave in CO_2 (**I**) and in N_2 (**II**). Wedge angle $\alpha_0 = 24^\circ$; shock-wave velocity $u_0 = 2100$ m/sec; initial pressure $P_0 = 12$ mm Hg.

I: SA—undisturbed part of the incident shock wave; AM—Mach wave; SRO—reflected wave with a kink at point R; AT—tangential discontinuity; L—scale mark. The first frame corresponds to time 23.3 μsec from the start of flow around the wedge. The time between successive frames is 4 μsec; exposure time 0.5 μsec.

II: SA—undisturbed part of the incident wave; ANO—reflected wave; AM—Mach wave; AT—tangential discontinuity curling into a vortex; L—scale mark. The first frame corresponds to time 14.5 μsec from the start of flow around the wedge.

point, as well as the values of the reflection angles ω_2, made it possible to test the applicability of the three-shock theory in the vicinity of the triple point.

The calculations were carried out by the method of shock polars, taking into account physicochemical transformations in the gas behind the shock waves. Information on the times

relaxation and the state of the gas behind the incident and reflected waves and the Mach wave (gas temperature of the order of $1000 \div 4000^\circ$ K for different incident-wave velocities, pressure of the order of $0.5 \div 5$ atm) were obtained from

Fig. 2

Figure 1: Fig. 2

literature data ($^{5-8}$), and also directly from experimental data on measurements of the angle of the attached wave, obtained simultaneously with the pattern of Mach reflection during diffraction of the wave on a wedge.

Comparison of the calculated and experimental values of the reflection angles $\omega_2 = \omega_2(\omega_1, u_0)$ confirms the validity of applying the three-shock theory. Figure 2 gives the calculated dependences $\omega_2 = \omega_2(\omega_1)$ under various assumptions about the state of the gas in the regions bounded by the waves that make up the Mach configuration, and experimental values of the angles ω_2 for a series of experiments on the reflection of shock waves in CO_2 with velocities close to 2000 m/sec. At these incident-wave velocities the gas temperature behind the waves is such that the dissociation time of CO_2 molecules exceeds the observation time of the reflection process (^{6}), while the time for excitation of molecular vibrations (except for asymmetric valence vibrations) is considerably less than this time (^{5}). The experimental values of the reflection angles are in satisfactory agreement with the curve calculated under the assumption of no dissociation and complete excitation of the vibrations of the gas molecules (curves 3 and 4 in Fig. 2). The calculated values of ω_2 for the case in which excitation of asymmetric valence vibrations is not taken into account lie somewhat above curves 3 and 4, and, since the difference in the value of ω_2 does not exceed the experimental error, the corresponding curves are not shown in the figure.

Fig. 2. Dependence of the reflection angle ω_2 on the angle ω_1 of a shock wave propagating in CO_2. The curves were calculated under the following assumptions about the state of the gas in all regions of the triple configuration: the ratio of specific heats is constant, $\gamma = 1.4$, $u_0 = 1900$ m/sec (1); $u_0 = \infty$ (2) (curve 2 taken from work (^{4})); all modes of gas vibrations are excited, dissociation has not occurred: $u_0 = 1900$ m/sec (3); $u_0 = 2100$ m/sec (4). The experimental points correspond to the velocities of the incident waves in the range $1900 \div 2070$ m/sec.

Physicochemical transformations in the gas lead to a decrease in the adiabatic exponent γ. We can obtain curves 3 and 4 if the state of the gas behind the incident and reflected waves and the Mach wave is determined with the aid of the ordinary shock adiabat, assuming that the effective adiabatic exponent is $\gamma = 1.19$.

A decrease of γ from 1.4 (curve 1 in Fig. 2) to 1.19 leads to a sharp change in the position of the reflected wave near the triple point; the values of the reflection angle ω_2 pass into the negative region. For a gas with a constant ratio of specific heats $\gamma = 1.4$, even at an infinitely large incident-wave velocity, the values of the angles ω_2 are positive (curve 2 in Fig. 2).

The schemes of gas flow near the triple point for cases of positive and negative

Fig. 3. Diagram of gas flow in the neighborhood of the triple point in Mach reflection in the coordinate system associated with the triple point.

Figure 2: Fig. 3. Diagram of gas flow in the neighborhood of the triple point in Mach reflection in the coordinate system associated with the triple point.

values of the angle ω_2 are given in Fig. 3.

Since the diffraction pattern of waves on a wedge represents a combination of Mach reflection and flow around an angle by a supersonic stream, it is necessary that the reflected wave pass into the attached wave. For negative values of the angle, a smooth transition is impossible even in the case where the leading edge of the wedge is moved to infinity, i.e., the case of Mach reflection without a disturbing

signal from the leading edge. Thus, a kink in the reflected wave is an inevitable consequence of the fact that the angle ω_2 takes negative values under any reflection conditions (from a half-plane or a wedge). In the case when $\omega_2 > 0$, a smooth matching of the attached and reflected waves is geometrically possible. Nevertheless, as experiment shows, such matching is not always realized, and a kink is formed in the reflected wave.

Fig. 3. Diagram of gas flow in the neighborhood of the triple point in Mach reflection in the coordinate system associated with the triple point. OA is the line of motion of the triple point; SA is the incident wave; RA is the reflected wave; AM is the Mach wave; AT is the tangential discontinuity; θ is the angle of flow deflection in passing through the wave; ω_1 is the angle of incidence; ω_2 is the angle of reflection. a: $\omega_2 > 0$; b: $\omega_2 < 0$.

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Note: Figure translations are in progress. See original paper for figures.