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Figure 2

Figure 1: Figure 2

Abstract

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ON THE DIFFRACTION OF A MULTI-FRONT DETONATION WAVE

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The basic laws governing the diffraction of detonation waves in gases must be considered from the standpoint of the real structure of the flow at the front, i.e., taking into account the existence of transverse waves. The present paper describes experiments that clarify a number of features of the process by which a detonation wave emerges from a channel of constant cross section into a volume of gas under conditions of a clearly expressed multi-front character of the detonation. We note that

Fig. 2. Successive stages of the contour of the shock front of the detonation (from schlieren photographs). Cases *a* and *b* correspond to Figs. 1*a* and 1*b*; *v* is for frames of Fig. 3.

separation of combustion from the shock front during diffraction was observed in (^{1}), and certain questions concerning allowance for the multi-front character of detonation in determining critical conditions were considered in (^{2}) as applied to liquid explosives.

Figures 1*a* and 1*b* show photographs of the trajectories of transverse waves in a plane channel when the width of the channel is abruptly increased. In the first case the propagation of the detonation is disrupted, whereas in the second it is maintained. The experiments differ in the initial pressure of the mixture ($C_2H_2 + O_2$). The positions of the diffracting front at successive instants of time, obtained by frame-by-frame schlieren photography, are shown for the same cases in Figs. 2*a* and 2*b*.

The initial stage of the process develops identically in both cases. Losing support from the flanks, the burned gas begins to expand sideways and creates shock waves in the adjacent fresh mixture. Let us estimate the range of variation of pressure and temperature at different points of the shock front in the initial stage of diffraction for a 90° step. As can be seen from the photographs, there is a continuous transition from detonation values (at the center of the wave) to certain minimum values corresponding to the parameters of the outer portions of the shock-wave front propagating perpendicular to the axis of the main channel. This lower limit is of interest for estimating the ability of the most weakened portions of the shock front to ignite. The front velocity in this region is established rather rapidly and decreases slightly as the front expands. Figure 1*v* shows a sweep photograph of the glow accompanying the emergence of a detonation wave from a round tube into a volume, taken "from the end," through a slit along the tube diameter. As analogous schlieren photographs showed, the expanding luminous trace—the flame front—gradually lags behind the shock front.

Naturally, the parameters of such a wave can be calculated on the basis of the scheme of decay of an arbitrary discontinuity (for simplicity of calculation a one-dimensional scheme was used). In Table 1 the calculated data for various mixtures are compared with measurements of the velocity of the shock wave along the wall perpendicular to the side wall of the channel. The table also gives the calculated values of the velocity behind the shock wave and the measured flame velocities.

Table 1

Mixture composition	Initial pressure, atm	Wave velocity, calculation	Wave velocity, experiment	Flow velocity behind the wave, calculation	Flow velocity behind the wave, experiment	T_{sw}, °K	T_{ign}, °K
$2CO + O_2 + 4\% H_2$	0.35	918	895	600	695	616	1260
$H_2 + O_2$	0.15	1160	950	605	–	515	850
$CH_4 + 2O_2$	1	1210	1140*	890	–	750	1250
$C_2H_2 + O_2$	0.07	1315	1100	890	930	695	700

* According to data of (^{1}).

The difference between them is of the order of the normal burning velocity in the shock-compressed gas. If one takes into account the idealized character of the calculation carried out, one can be convinced of the validity of the estimate made for the upper bound of the parameters of the outermost portions of the shock-wave front. From the data given it is evident that the temperature in these portions of the wave is, as a rule, considerably lower than the self-ignition temperature of the gas with a delay of less than 10^{-3}–10^{-4} sec (see Table 1). Only for the acetylene-oxygen mixture is this difference small. Thus, the position of the flame front behind the portion of the shock front under consideration is determined not by self-ignition delays, but by mixing of the gas particles and by the normal burning velocity.

Table 2

D_n, km/sec	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.2
T_2, °K	655	745	845	940	1050	1160	1270	1400	1540	1650	1810	1950	2230
p_2/p_1	8.0	10.0	12.1	14.5	17.0	19.7	23	26.5	30.5	33.8	37.6	41.8	50.2
ρ_2/ρ_1	3.55	3.9	4.23	4.5	4.8	5.04	5.23	5.49	5.68	5.85	6.0	6.1	6.3
τ, μsec					500	300	79.5	12.5	5.5	1	1	–	–

When moving along the shock-wave front in the direction away from the wall, the wave parameters (velocity, pressure, temperature) gradually increase, reaching, in the region of coalescence with the still undisturbed detonation front, values corresponding to the detonation velocity. The portion of the front directly adjoining the undisturbed front is of greatest interest for determining the critical conditions for the emergence of detonation without decay. To understand the processes taking place on it, it is first necessary to consider the structure of the undisturbed portion of the front.

As has been established ([3], [4]), the detonation front in gases is covered with transverse disturbances—waves that exert a substantial influence on the mechanism of detonation compression. Figure 3 gives a frame-by-frame photograph of the diffraction of a detonation front in a mixture $2CO + O_2 + 4\% \; H_2$ with two transverse waves (t. w.). The successive positions of the fronts corresponding to these frames are given in Fig. 2b. The diffraction patterns indicate the velocities of the corresponding portions of the leading front, in kilometers per second in the direction of the normal. The corresponding temperatures T_2 behind the front, as well as the pressure p_2/p_1, compression ρ_2/ρ_1, and ignition delays τ, are given in Table 2. The temperature behind the transverse fronts before collision, calculated from the photographs, is about 1700° K, and the pressure about $90p_1$. The collision of the t. w. here occurs outside the zone of action of the rarefaction waves.

To the article by V. V. Mitrofanov and R. I. Soloukhin

Fig. 1. Trajectories of transverse waves at the emergence of detonation in a mixture of acetylene with oxygen:
a –plane channel, method (3), $p_1 = 73$ mm Hg ($C_2H_2 + 2.5O_2$); *b* –the same, $p_1 = 78$ mm ($C_2H_2 + 2.5O_2$); *c* –round tube, end-on scanning, $p_1 = 24$ mm ($C_2H_2 + O_2$)

Fig. 3. Schlieren photographs of diffraction in a mixture $2CO + O_2 + 4\%H_2$. Filming rate 281 thousand frames per second

Fig. 4. Detonation of a mixture $2CO + O_2 + 4\%H_2$ in a plane channel of constant cross section

The structure of T.W. was considered in detail in works (3,5). Here we shall note only a few points. In the photographs the boundary between the initial and the burned mixture is clearly visible. Ignition with small delays (of the order of 1 μsec and less) occurs behind the transverse fronts and the "breaks" of the leading front. Between converging T.W., the temperature behind the leading shock front is 940°K; therefore the gas, not having time to autoignite, is swept up and burned by the T.W. It should be noted that, in multifront detonation, the parameters of the T.W. are such that the gas in them ignites "at the limit," i.e., over distances comparable with the width of the transverse front. In the mixture $2CO + O_2 + 4\% H_2$, the temperature behind the "mean" transverse front before an opposing collision is about 1500°K (3), which corresponds to ignition delays of several microseconds. Therefore, behind transverse fronts weaker than the "mean" one, autoignition practically ceases (5), and individual portions of the mixture that have passed through such T.W. ignite only after collision with an opposing wave, or even detach from the front and then burn out by means of the usual mechanism of flame propagation. These processes can be observed in Fig. 4, where several frames of detonation propagation in a flat channel of constant cross section are presented. Behind the "breaks" of the leading front the temperature is somewhat higher than behind the transverse front, and the ignition delays are correspondingly smaller. As a result of an opposing collision, weakened T.W., as a rule, are strengthened and their igniting ability is restored. Behind transverse fronts stronger than the mean, combustion occurs in a narrow layer, as we see, for example, in Fig. 3.

After collision and mutual refraction, the newly forming T.W. (the 5th frame in Fig. 3) emerge onto the weakened lateral-unloading section of the front and, not encountering waves of the other direction, are themselves weakened so much that the reaction behind them ceases. The temperatures behind the leading front by this moment everywhere become insufficient for rapid ignition of the mixture (see Fig. 2e and Table 2), and the detonation dies out. An analogous process occurs on the weakened flanks of the diffracting detonation front also when there are many T.W. From the photographs in Fig. 1 we see that the central section of the front, on which opposing collisions of T.W. exist, always narrows in the initial stage of diffraction, since after emergence the reflection of the outer T.W. from the side walls ceases. Onto the sections of the front adjoining the flanks, T.W. from the central region emerge in only one direction. Having undergone the last collision, the T.W. emerging onto the section under consideration initially passes through the same stages of development as any T.W. between successive collisions in the central region. Subsequently, not undergoing collisions, this T.W. must, generally speaking, weaken.

From the results of work (5) it follows that a system of T.W. of one direction in the plane case is apparently unstable, i.e., it either dies out or breaks up, giving rise to waves of the other direction. For a continuous transition of detonation from a narrow channel into a wide one, it is evidently necessary that, on the weakened flanks with T.W. of only one direction, conditions be created for the generation of waves of the opposite directions. The generation of new T.W. is evidently connected with the instability of the gas autoignition front (^{6}).

Since, in the section adjoining the central undisturbed region, the parameters of the leading shock wave approximately correspond to the detonation velocity, it may be assumed that the determining critical quantity for the generation of new T.W. may be the radius of curvature r of the front or, more precisely, its ratio to some characteristic length l characterizing the extent of the reaction zone behind it. To estimate the critical value of this ratio one may use a criterion of type (^{6}), assuming that extinction of the reaction behind the shock front will occur in the case when the change in ignition delays behind the curved-

due to the temperature gradient will be of the order of the magnitude of the delay itself:

$$\Delta\tau \simeq \frac{d\tau}{dT}\,\frac{dT}{dr}\,l \gtrsim \tau.$$

Assuming $dT/dr \sim 2T/r$ and $\tau = \tau_0 \exp(E/RT)$, we obtain the condition for attenuation: $l/r \gtrsim RT/2E \simeq 2\cdot 2000^\circ/2\cdot 20000 = 0.1$. The radius of curvature r of the portion of the front under consideration increases with time. For the case of attenuation, taking $r_{\max} \simeq \dfrac{D}{2c} d \sim 09\,d$, where d is the channel width (or tube diameter), and estimating $l \sim d/n$, where n is the average number of detonation waves in one direction in a plane channel (or along the tube diameter), we obtain $n \lesssim 10$. Despite the approximate nature of the calculations presented, the critical number n obtained agrees with experiments ($n \sim$ 10–13 in Fig. 1; see also (^{3,7})) in a plane channel. For transition from a round tube into a volume (Fig. 1b), $n_{\mathrm{cr}} \simeq 13$.

If $n > n_{\mathrm{cr}}$, the detonation after emerging from the channel (or tube) becomes cylindrical (spherical). It is characteristic that, in the direction perpendicular to the channel, detonation is restored only after about 10 detonation waves have emerged onto the curved flank (see Figs. 1 and 2). This explains the delays in the occurrence of detonation in the indicated direction observed in work (^{7}).

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