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A. A. BORISOV, S. M. KOGARKO

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A. A. BORISOV, S. M. KOGARKO

ON CERTAIN STUDIES OF SPIN DETONATION

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The acoustic theory of spin detonation (^{1}) cannot be regarded as a theory that satisfactorily explains this phenomenon. Indeed, those terminal disturbances, expressed in breaks of the shock front, which appear in spin detonation, in no way follow from it (^{2}). Naturally, in order to understand more fully the structure and mechanism of spin detonation, it is necessary to study not so much the wave motions in the burned gas as their connection with the motion of waves in the zone between the shock front and the reaction zone, since it is most likely precisely what occurs in this zone that serves as the primary cause of the phenomenon. The principal works on the study of spin detonation were devoted precisely to clarifying the gas-dynamic structure of the motion in the zone between the shock front and the reaction front (^{2}, ^{3}). In the present work the form of this zone and the state of the gas in it were studied by the trace method.

Studies of high-temperature kinetics in shock waves (^{4}) have shown that the process of heat release at high temperatures proceeds explosively, with a clearly expressed ignition-delay period. In a spin detonation wave there is a shock wave heating the gas to a high temperature; therefore it is quite natural to assume that the reaction here will proceed in the same way as in the ignition of a gas by shock waves reflected from a rigid wall, i.e., to consider that the reaction zone may be characterized by a rather broad region of unburned gas (ignition delay) and a very narrow reaction zone (ignition), with the difference from the usual model of a detonation wave (^{5}) that the temperature in different stream tubes across the cross section of the tube is different. The latter follows from the fact that the front of the shock wave driving the spin detonation is not plane (^{2}).

The experiments were carried out with mixtures of $CH_4 + 2O_2$ at pressures P_0 –30 mm Hg in a tube of internal diameter 65 mm and length 4 m. The wave was initiated by burning the same mixture at atmospheric (or higher) pressure, in small volumes separated from the main tube by a diaphragm. The motion of the waves was observed by the trace method (2) (the traces were left on a smoked film inserted inside the tube). The velocities of the detonation waves were measured with ionization probes. As was observed by direct photography and by the trace method, ignition of fuel-oxygen mixtures by reflected shock waves is accompanied by the formation of a multiheaded or pulsating detonation wave. A fine network of traces of an overcompressed detonation wave with a large number of heads also appears on trace records of the transition of fast combustion to detonation (at the initial moment of time the detonation wave being formed has an increased velocity). Thus, an overcompressed detonation wave will always leave on the smoked walls of the tube a network of traces, and the greater the degree of overcompression, the finer this network. If behind the shock front of a spin detonation wave there exists a region of unburned gas, then when it collides with an overcompressed detonation wave or with a rigid wall, one should expect in this zone the appearance of a detonation wave, strongly overcompressed, with a large numbe-

of fronts (a refracted detonation wave or, in the case of reflection from a rigid wall, a reflected one). Figure 1 shows the collision of a spin wave propagating from below at a velocity of 1900 m/sec with an overcompressed one propagating from above at a velocity of 2400 m/sec. Line *I* is the result of the collision of the shock fronts; region *II*, with a very fine network of traces, is precisely the region of unburned gas behind the spin detonation wave (as we suppose, the ignition-delay region); region *III* is burned gas.

To determine the lengths of the zone of unburned gas behind the shock front along the periphery of the tube, it is necessary to know the propagation velocity of the refracted detonation wave in the laboratory coordinate system. With the accuracy required for calculating ignition delays, the colliding waves may be regarded as plane waves, so that for the velocity of the refracted wave we obtain the following system of equations:

$$M_{sd} = \frac{D_{sd} + W_s}{c_s},$$

$$\begin{aligned}
& -W_s - W_d + c_s M_{sd} + \left\{ \frac{P_s}{P_d} \frac{\gamma_s}{2\gamma_d} M_{sd}^2 \left[1 + \Delta - \frac{\gamma_d}{\gamma_s M_{sd}^2} \right] \right. \\
& \qquad \left. + \frac{\gamma_d + 1}{2\gamma_d} \left(\frac{P_s}{P_d} - 1 \right) + 1 \right\}^{1/2} c_d \\
& = \frac{W_s + M_{sd} c_s}{\gamma_d + 1} \left[\gamma_d - \Delta + \frac{\gamma_d}{\gamma_s M_{sd}^2} \right] + \\
& + \left[W_d + c_d \left\{ \frac{P_s}{P_d} 2 \frac{\gamma_s}{\gamma_d} M_{sd}^2 \left[1 + \Delta - \frac{\gamma_d}{\gamma_s M_{sd}^2} \right] \right. \right. \\
& \qquad \left. \left. + \frac{\gamma_d + 1}{2\gamma_d} \left(\frac{P_s}{P_d} - 1 \right) + 1 \right\}^{1/2} \right] \times \\
& \times \left\{ \gamma_d - 1 + 2 \middle/ \left(\frac{P_s}{P_d} \frac{\gamma_s}{2\gamma_d} M_{sd}^2 \left[1 + \Delta - \frac{\gamma_d}{\gamma_s M_{sd}^2} \right] \right. \right. \\
& \qquad \left. \left. + \frac{\gamma_d + 1}{2\gamma_d} \left(\frac{P_s}{P_d} - 1 \right) + 1 \right) \right\} (\gamma_d + 1)^{-1},
\end{aligned}$$

where W is the gas velocity, c the speed of sound, P the pressure, γ the ratio of specific heats C_p/C_v, D_{sd} the velocity of the refracted wave; the subscript s refers to the gas behind the shock front of the spin detonation, and the subscript d to the gas behind the overcompressed waves,

$$\Delta \cong \left[\left(1 - \frac{\gamma_d}{\gamma_s M_{sd}^2} \right)^2 - \frac{2q\left(\gamma_d^2 - 1\right)}{c_s^2 M_{sd}^2} \right]^{1/2};$$

q is the heat of reaction.

The ignition delay in terms of the length of the zone of unburned gas can be expressed as follows:

$$\tau \cong \frac{l(\gamma_s + 1)}{(\gamma_s - 1) D_s};$$

D_s is the velocity of the spin wave. Figure 2 presents ignition delays obtained by processing one of the collision records (the delays were taken at different locations of the shock-wave front, inclined in different ways to the direction of propagation, i.e., at different temperatures) and in reflected shock waves at identical pressures before ignition*. As can be seen, the agreement is very good. Similar results were obtained by the authors (^{3}) for a mixture of carbon monoxide with oxygen. Thus, the method of colliding detonation waves immediately gives the temperature dependence of ignition delays, which is its great advantage over the method of reflected shock waves.

Fig. 2. Dependence of ignition delays on reciprocal temperature. *a*—delays in reflected shock waves, *b*—delays in the spin-detonation wave

Figure 1: Fig. 2. Dependence of ignition delays on reciprocal temperature. *a*—delays in reflected shock waves, *b*—delays in the spin-detonation wave

The region of unburned gas in spin detonation has, roughly speaking, the form of a triangle. At locations with the highest temperature the reaction zone has almost zero width, while at locations with the lowest temperature it reaches—

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* It was assumed that the temperature along the flow tube changes only slightly owing to the nonuniformity

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Fig. 1. Shadowgraph of the collision of a spin detonation wave with an overcompressed multi-headed one. *I* —collision of wave fronts, *II* —region of unburned gas behind the spin detonation wave, *III* —burned gas

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Fig. 1. Druse formations of lomonite. 1.5 natural size.

reaches values on the order of the tube diameter. Upon reflection of the spin-detonation wave from the closed end of the tube, such a triangular zone of unburned gas was observed not only at the periphery of the tube but also over the entire cross-section. In this case the sooted film was inserted either as concentric rings with a spacing of somewhat less than 1 cm from one another, or as a narrow strip at the center of the tube. To confirm the existence of a zone of unburned gas behind the shock front in spin detonation, we carried out special experiments with corona-discharge probes. The corona discharge between two needles placed at the center of the tube was blown out by the shock wave, and the electric current reappeared only after the ionized gas behind the ignition front reached the probe. The oscillograms of the current through the probe did indeed show the existence of a zone with zero current, of extent on the order of 30–50 μsec (the width of the zone being on the order of the tube diameter or somewhat greater).

Fig. 2. Dependence of ignition delays on reciprocal temperature. *a*—delays in reflected shock waves, *b*—delays in the spin-detonation wave.

The trace method also makes it possible to judge the Mach number of the main part of the flow behind individual sections of the wave front from the shock waves that arose on large soot particles and were imprinted on the sooted surface of the tube walls. The flow is supersonic in the laboratory coordinate system in the region of maximum length of the zone of unburned gas, as was to be expected for the flow of unignited gas behind a strong shock wave. As the size of the zone of unburned gas decreases, the sharpness of the imprints of the shock waves also decreases, since the latter simply do not have time to be imprinted well before the subsonic flow of the reaction products reaches the particle. The absence of shock waves in the region of the kink, where the shock wave propagates through the gas with a velocity exceeding that calculated from the Jouguet condition, and where the flow velocity of the reaction products in the laboratory coordinate system should be somewhat above the speed of sound, can be explained by the fact that immediately after the kink there follows a rarefaction wave, which decelerates the gas. Thus, in the laboratory coordinate system the gas flow in this region is predominantly subsonic.

Thus, the existence of a zone of unburned gas behind the front of the shock wave leading the spin-detonation wave has been established experimentally, and it has also been shown that the reaction front is the front of autoignition of gas heated by the shock wave. The reaction front, in places where the normal component of the gas inflow velocity into the shock wave is maximal, comes almost right up to the shock front, while in places where this component of the velocity is minimal (and the gas temperature is also minimal), it recedes from the shock-wave front by a distance on the order of the tube diameter.

Institute of Chemical Physics
Academy of Sciences of the USSR

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