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INITIATION OF DETONATION IN REFLECTION OF A SHOCK WAVE FROM A CONCAVE CURVILINEAR SURFACE

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The authors present results of investigating the possibility of initiating a detonation regime of combustion of reactive gaseous mixtures by focusing a plane shock wave in reflection from concave axisymmetric and two-dimensional surfaces.

Shock wave initiation of detonation processes has repeatedly been the subject of both theoretical and experimental investigations [1-6]. At the same time a local increase in the parameters in the region of the gasdynamic focus that is formed in reflection of a plane shock wave from a concave curvilinear surface [7] permits a substantial reduction in the limits for initiation of detonation [8–10].

The present authors report results of investigating the possibility of initiating a detonation regime of combustion of reactive gaseous mixtures by focusing a plane shock wave in reflection from concave surfaces, both axisymmetric and two-dimensional ones.

A gasdynamic stand for carrying out experiments with an axisymmetric model was based on a two-diaphragm shock tube with a nonstationary flow expansion [11]. The diameter of the low-pressure chamber and the intermediate section was 76 mm; the module under investigation with a spherical recess of radius 36.7 mm and depth 28.7 mm was located at the end of the shock tube. The dynamics of pressure change was recorded in different cross sections by precalibrated piezoelectric pressure transducers with a spatial resolution of 3 mm. The gas parameters were calculated using a shock adiabat from the shock wave velocity measured by the time delay of signals from piezoelectric pressure transducers located on two different bases. Furthermore, the magnitude of the pressure behind the incident and reflected shock waves both in the cavity itself and in front of it was controlled by calibrated pressure transducers located in the spherical end wall on the channel axis and in the side wall at a distance of 30 and 205 mm from the cavity section. Primary signal recording was performed using S9-8 digital oscillographs: further processing of results of measurements as well as recording of the shock wave velocity and calculation of thermodynamic parameters of the medium were carried out with the use of an automated system for acquisition and processing of experimental data made on the CAMAC standard based on an "Elektronika MS-1212" minicomputer connected with an IBM PC/AT-286 type central personal computer.

In the course of the experiments we determined the minimum intensity of the shock wave that initiates a detonation regime of combustion of the mixture in question. It is evident that the conditions under which detonation is initiated are determined not only by the magnitude of the energy contributed to the reactive gas but also by the time of energy contribution, i.e., the power [1–5].

For the incident plane shock wave that is the "detonator" the energy and power contributed to unit area of the reactive mixture are determined by the simple expressions [12]

$$W = P_2 U_2 d\,, \quad E = Wt\,.$$

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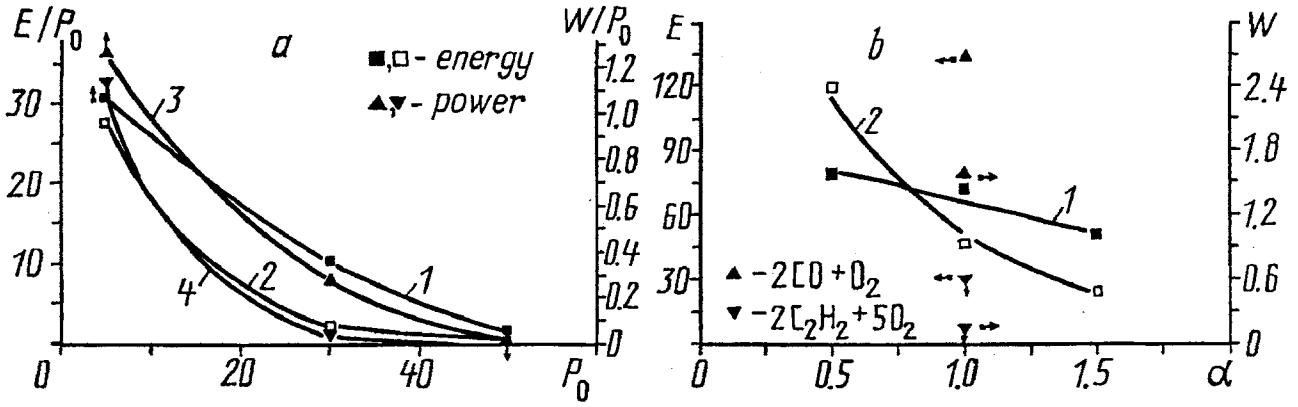

Fig. 1. Minimum energy and power of the shock wave "detonator" resulting in the detonation regime of combustion of a hydrogen-oxygen mixture vs initial pressure (kPa) (a) and excess-oxidant coefficient (b): 1, 3) normal reflection; 2, 4) reflection from a spherical cavity. E/P_0, J/(m^2·Pa); W/P_0, MW/(m^2·Pa); P_0, kPa; E, kJ/m^2; W, GW/m^2.

Here P_2, U_2 are the pressure and velocity of the gas behind the front of the shock wave propagating in the low-pressure chamber of the shock tube; d is its cross-sectional area; t is the time in which the energy is supplied. As shown in [13], this time corresponds to the induction period for the parameters realized on the contact surface. We note that in this case the "detonator" power increases as the shock wave intensity increases, but the energy decreases.

It can easily be shown that for a shock wave that passes through a low-pressure chamber of length L_0 filled with the mixture in question and is normally reflected from a plane rigid end the energy contribution to the reactive mixture is

$$E = P_5 T_5 L d / T_1 - P_1 L_0 d .$$

Here $L = L_0 V_5 (V_1 - V_2)/V_1 (V_5 + V_2)$ is the length of the plug of gas compressed behind the reflected shock wave, i.e., the distance from the end to the cross section where the reflected shock wave and the rarefaction wave fan meet; P_1, T_1 are the initial pressure and temperature; P_5, T_5 are the pressure and temperature behind the reflected shock wave front; V_1, V_5 are the velocity of the incident and reflected shock wave, respectively. For this energy supply the "detonator" power will be $W = E/t$, where $t = \min(t_i, t_r)$, $t_i = 1.825 \cdot 10^{-16} T/(P \xi_{O_2} \exp(7650/T)$ [14] is the induction period for the parameters realized at the reflecting end, $t_r = L_0 (V_1 - V_2/V_1 (V_5 + V_2)$ is the time in which the reflected shock wave traverses the distance L. In this case, unlike initiation of detonation behind incident shock waves, both the energy and the power increase as the shock wave intensity increases.

In connection with the fact that, in investigating shock wave initiation of detonation in a chamber separated by a thin diaphragm, the problem is multiparametric (the shock wave intensity, the initial pressures and compositions of the gases in low-, intermediate-, and high-pressure chambers, the lengths of the corresponding chambers of the shock tube, etc.), we will subsequently operate with two characteristics, namely, the energy and power supplied to the mixture in question, which in turn are uniquely determined by the aforementioned parameters.

As the dependences of Fig. 1a show, the curvature of the reflecting surface decreases substantially both the energy and power limits of initiation of the detonation combustion regime. Our recorded reduction in the limits of initiation of detonation with increase in the pressure is in agreement with results of investigating the condition under which the detonation regime of combustion is initiated in reflection from an interior angle [10]. The reduction in the limits of initiation of detonation as the oxygen concentration increases in a hydrogen-oxygen mixture (Fig. 1b) agree with results of [15]. A comparative analysis of stoichiometric mixtures of acetylene, hydrogen, and carbon

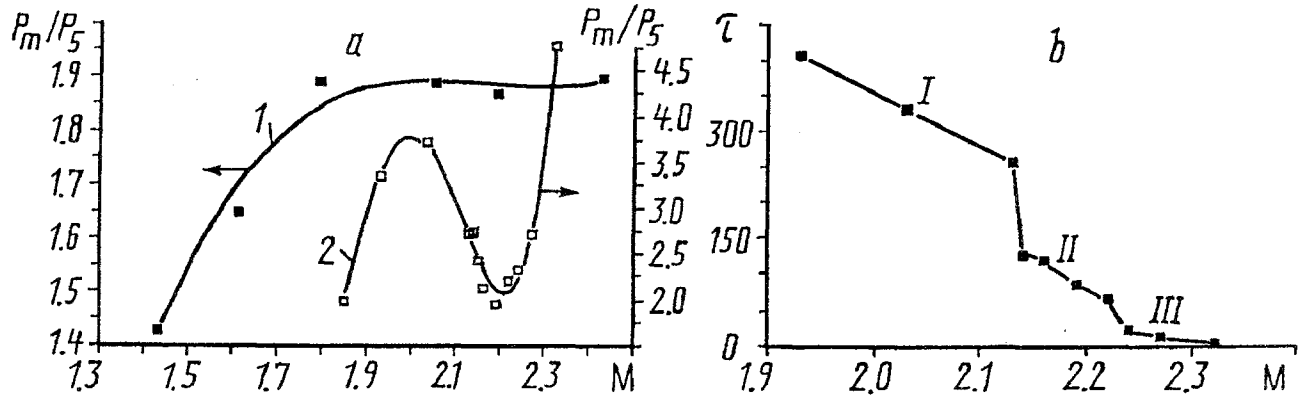

Fig. 2. Degree of focusing for air (1) and a stoichiometric hydrogen-oxygen mixture (2) (a) as well as ignition delay (b) vs Mach number of the incident shock wave. τ, μsec.

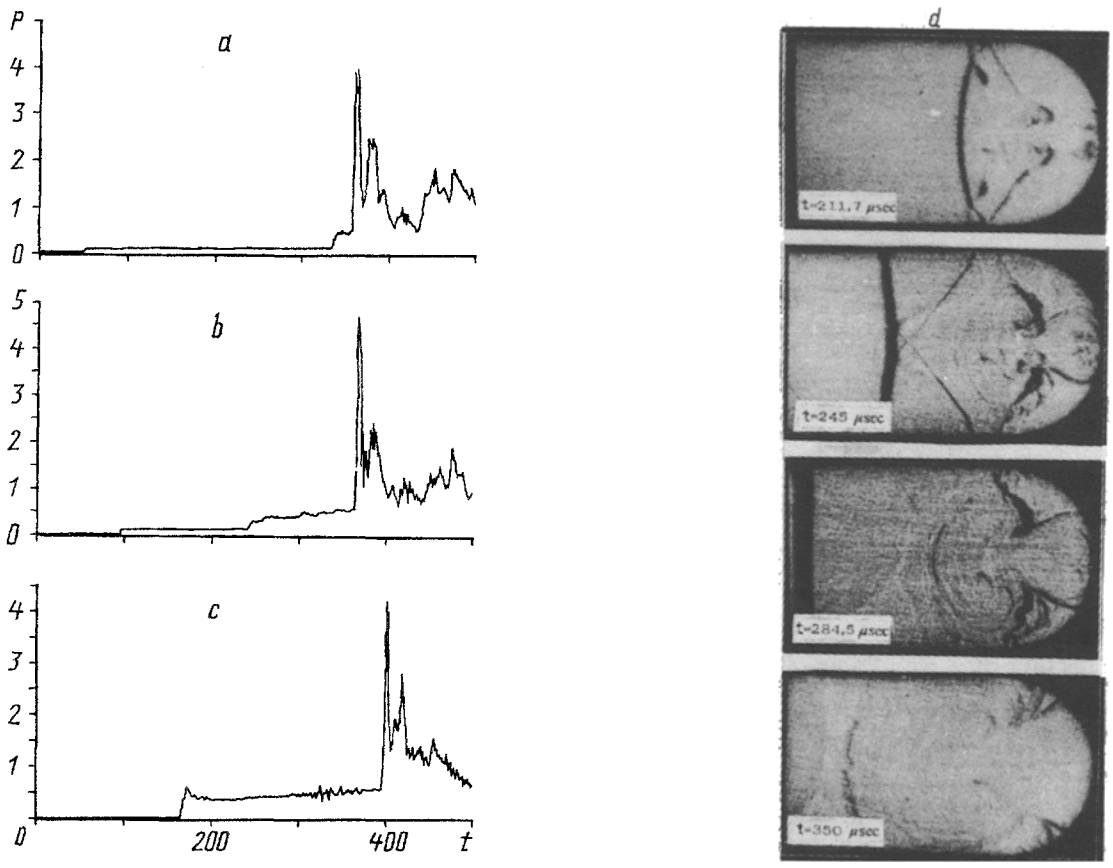

Fig. 3. Traces of the change in pressure (a, b, c) and shadow photographs (d) of shock wave initiation of detonation in a stoichiometric hydrogen-oxygen mixture for the Mach number of the incident shock wave $M = 2.07$; the initial pressure $P_1 = 20$ kPa. P, MPa; τ, μsec.

monoxide with oxygen shows that to initiate the detonation regime of combustion of the last one the consumption is maximum while for that of the first one it is minimum.

Experiments with a two-dimensional concave reflecting surface were carried out on a one-diaphragm shock tube with a channel of the low-pressure chamber of cross section 45 × 90 mm, at the end of which a concave cylindrical cavity of radius 22.5 mm was mounted. The recording system was similar to the one described above. Furthermore, with the use of an IAB-451 shadow instrument combined with a high-speed photorecorder based on

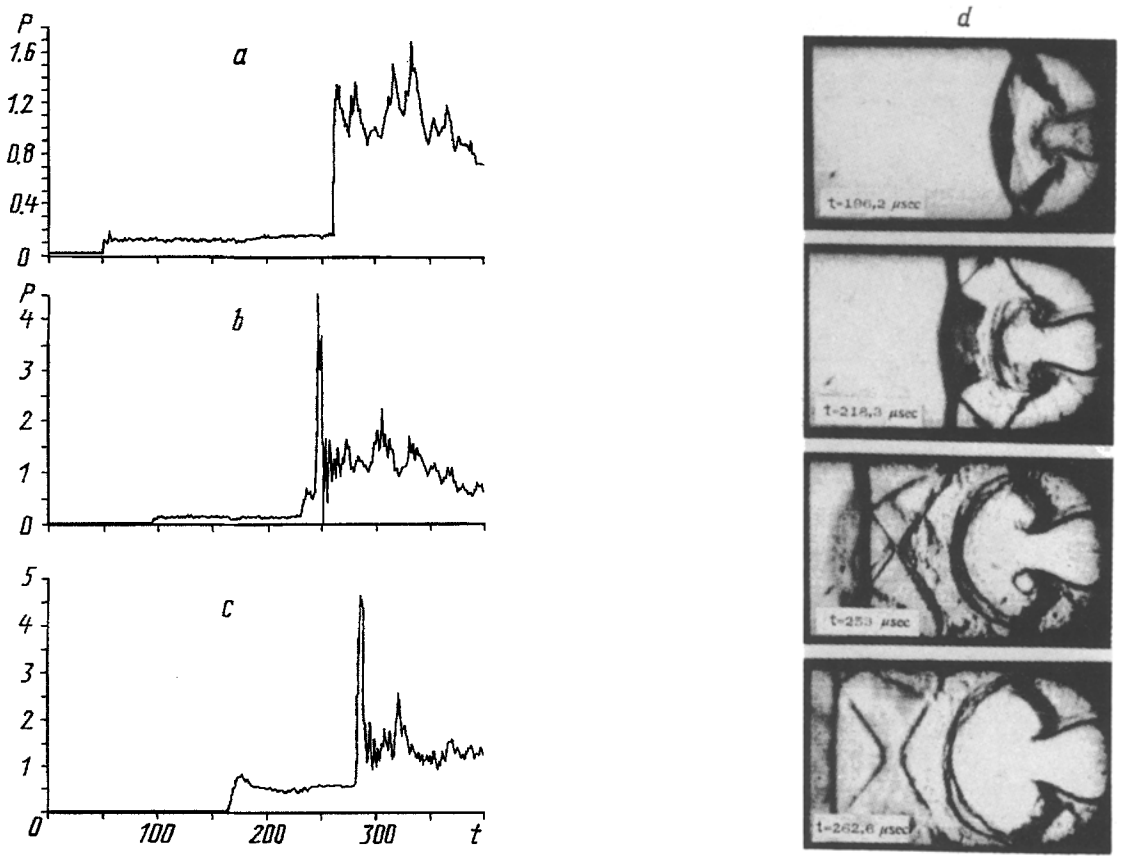

Fig. 4. Traces of the change in pressure (a, b, c) and shadow photographs (d) of shock wave initiation of detonation in a stoichiometric hydrogen-oxygen mixture for the Mach number of the incident shock wave $M = 2.165$; the initial pressure $P_1 = 20$ kPa.

a ZhLV-2 driven time magnifier, visualization of shock wave initiation of detonation processes in the cavity was carried out in some, characteristic, regimes. For synchronized start-up of the shock tube and also to eliminate the hindering effect of diaphragm scraps, use was made of a diaphragmless high-pressure chamber with forced electropneumatic start-up.

In reflection of a plane shock wave from a concave cylindrical surface the peak value of pressure on its bottom P_m exceeds substantially the value of the pressure that corresponds to normal reflection from a plane wall P_5 (Fig. 2a). In this case, for nonreacting media, starting with $M \simeq 2$ an increase in the Mach number of the incident shock wave does not result in a substantial change in the degree of focusing P_m/P_5. For chemically reacting mixtures (in our case $2H_2-O_2$) this dependence has a fundamentally different character (Fig. 2a). For $M < 2$ we observe an increase in P_m/P_5 with increase in M as in the case of a nonreacting gas; however, a further increase in the Mach number results in a sharp decrease in the degree of focusing, which attains a minimum value at $M \simeq 2.19$, which is apparently due to focused shock wave energy consumed by initiation of chemical reactions. As the Mach number increases further, the degree of focusing increases gradually, which is associated with the development of the reaction in the region behind the reflected shock wave, and starting with $M = 2.27$ there is a sharp increase in the degree of focusing, due to initiation of detonation directly in the gasdynamic focus. This is confirmed by results of high-speed photorecording.

The ignition delay (the time between the first and the second pressure peaks recorded at the cavity bottom) given in Fig. 2b as a function of the Mach number permits differentiation of several characteristiic zones. In zone I, ignititon occurs behind the front of the reflected shock wave with a substantial delay, and in this case a detonation wave moves toward the semiclosed cavity through an almost nonreacted mixture. The dynamics of the development of this process is illustrated in Fig. 3 by results of frame photorecording and traces of the change in pressure at

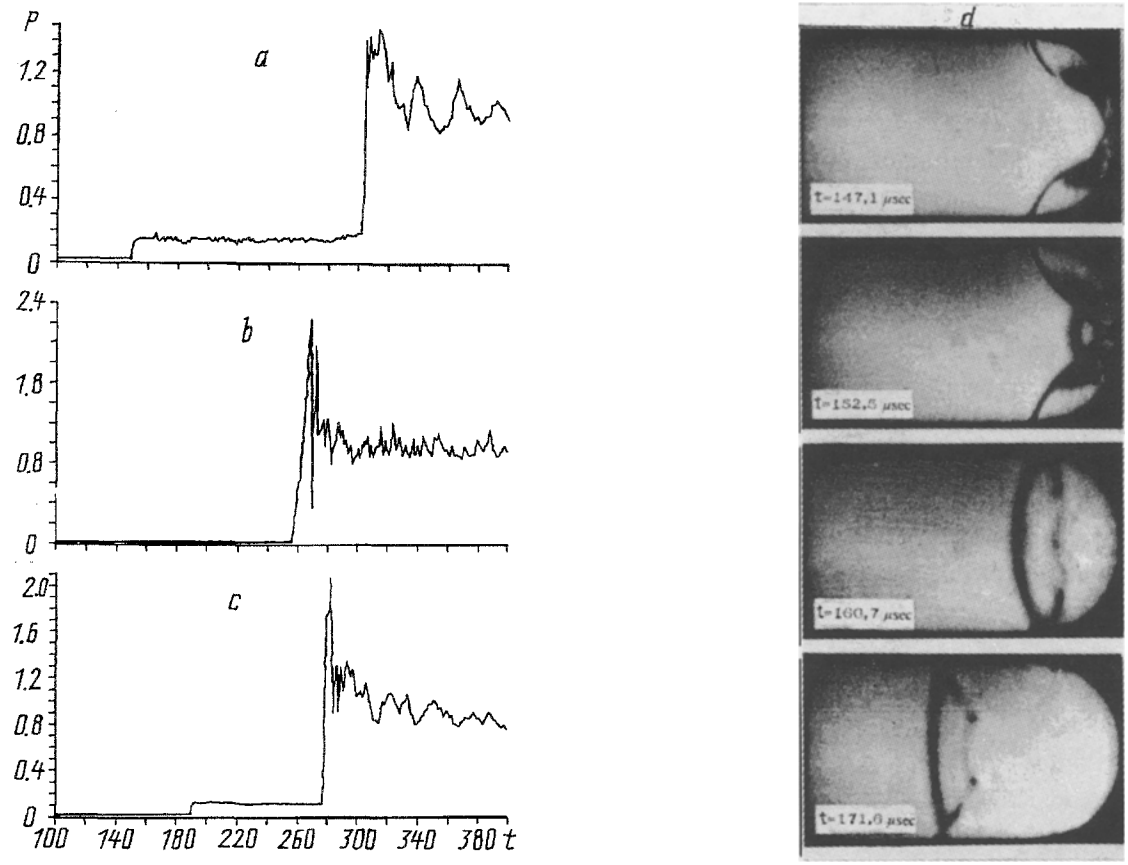

Fig. 5. Traces of the change in pressure (a, b, c) and shadow photographs (d) of shock wave initiation of detonation in a stoichiometric hydrogen-oxygen mixture for the Mach number of the incident shock wave $M = 2.34$; the initial pressure $P_1 = 20$ kPa.

the semiclosed cavity bottom (c) and on the side wall of the channel at a distance of 57.5 (b) and 109.5 mm (a) from the bottom. Hereinafter, recording of pressure was begun 50 μsec before the shock wave's arrival at piezoelectric pressure transducer *a*. As Fig. 3d shows, by the time $t = 211.7$ μsec the incident plane shock wave has already been focused and formation of the reflected shock wave occurs, behind the front of which the reaction zone expands (shadow photographs corresponding to $t = 245$ and 284 μsec). By the time $t = 355$ μsec a detonation wave that is initiated, judging from the difference in the times of its arrival at pressure transducers *a*, and *b*, at a site between them in a volume of gas that is heated and compressed behind the reflected shock wave front propagates to the second transducer. Subsequently, this detonation wave is focused, having reflected from the concave surface, and the shock wave structure formed propagates through the already reacted gas.

An increase in the Mach number of the incident shock wave to $\simeq 2.16$ (zone II, Fig. 2b) results in a reduction in the ignition delay to tens of microseconds, which is due to the development of the reaction zone already in formation of the reflected shock wave in the semiclosed cavity (Fig. 4d). In this case at $t = 253$ μsec two systems of detonation waves begin to propagate in the channel: a system that moves in the rectangular channel through gas that is heated and compressed only behind the incident shock wave front (Fig. 4a) and a system of collapsing detonation waves that propagate through the gasdynamic structure of reacting gas that is formed in reflection of the shock wave from the concave curvilinear surface (Fig. 4b and c).

A further increase in the shock wave intensity results in a reduction in the ignition delay to microseconds (zone III, Fig. 2b), the detonation regime of combustion being initiated directly in the zone of gasdynamic focusing (Fig. 5).

Thus, the curvature of the reflecting surface reduces substantially the power and energy limits of initiation of detonation. They are reduced in a hydrogen-oxygen mixture as the oxygen content increases. For initiation of

the detonation regime of combustion in stoichiometric mixtures of acetylene, hydrogen, and carbon monoxide with oxygen the energy consumption is minimum for the first mixture and maximum for the last mixture. The ignition delay and the degree of gasdynamic focusing in chemically reacting gaseous mixtures change nonmonotonically with a change in the Mach number of the incident shock wave, which is due to realization of different schemes for initiating the detonation regime of combustion.

NOTATION

E, shock wave "detonator" energy; L, length of the low-pressure chamber of the shock tube; M, Mach number of the incident shock wave; P_1, initial gas pressure in the low-pressure chamber of the shock tube; P_2, gas pressure behind the incident shock wave front; P_5, gas pressure behind the shock wave reflected from the plane wall; P_m, maximum peak value of the pressure at the bottom of the semiclosed cavity; T_1, initial temperature; T_5, gas temperature behind the shock wave reflected from the plane wall; U_2, gas velocity behind the incident shock wave front; V_1, incident shock wave velocity; V_5, reflected shock wave velocity; W, shock wave "detonator" power; d, cross-sectional area of the shock tube; t, time; t_i, induction period; a, excess-oxidant coefficient; τ, ignition delay.

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