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GAS IGNITION BEHIND THE SHOCK WAVE

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INTRODUCTION

Ignition of gas mixtures by means of shock waves has been studied in a number of experimental research laboratories[1–3]. The methods employed were either the schlieren photography or pressure registration by means of piezo gauges. In these experiments the main features of the phenomena accompanying the ignition of gas behind the shock wave have been determined (ignition delay, initiation of detonation followed by periodic pressure fluctuations). It is interesting to make a detailed analysis of the sequence of these phenomena and, among other things, to find out how the ignition of gas in the flow behind the shock wave is initiated and how the transition to detonation proceeds. In this connection the Combustion Physics Laboratory of the Institute of Energetics of the U.S.S.R. Academy of Sciences has carried out a number of experiments on the ignition of combustible gases in a shock tube. Experiments were also carried out to study the gas ignition behind the impinging shock wave and its interaction with the angular step.

DESCRIPTION OF THE DEVICE

To carry out the experiments a shock tube with a square cross-section of 40×40 mm was employed. The total length of the tube is 3–5 m with a 2 m interval between the high pressure block and the point of observation. A section of the tube 200 mm long, with glass side walls, was under observation. The shape and the size of the tube cross-section remained unchanged.

Density disturbances were registered by means of a schlieren apparatus IAB-451 on rotating films. The linear speed of the films varied from 30 m/sec to 120 m/sec.

A flash discharge tube with a flash duration of about 2–5 msec served as the source of light.

Along with the schlieren photography the pressure process was registered by an impulse piezo gauge made of a ceramic pile of barium titanate with a zinc branch rod, and wax sound insulation from the chamber walls.

The sensitive surface of the gauge formed part of the shock tube wall; and the signal was registered by means of an impulse oscillograph IO-IIIV.

Fig. 1 shows typical moving image photographs of a current, initiated after breaking the diaphragm in the shock tube. The photograph was taken at a distance of 2 m from the diaphragm, with air at a pressure of 0.01 kg/cm^2 in the low pressure chamber.

Fig. 2 shows the oscillogram of pressure in inert gas. As is shown in the photograph, throughout the whole space the contact surface including the pressure varies insignificantly. The illustrations show the resolving power of the registering apparatus.

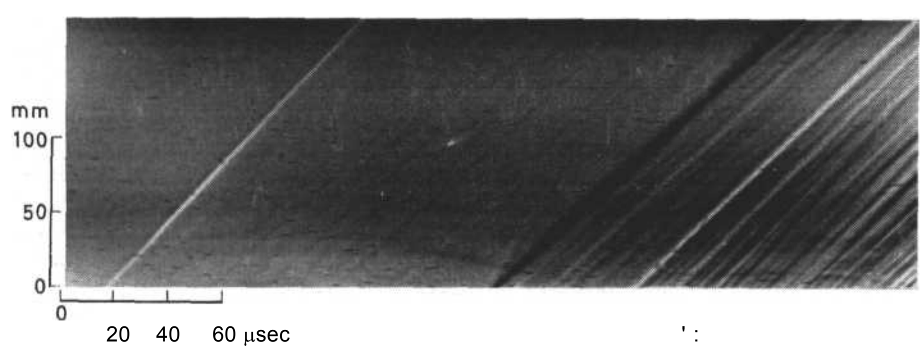

Fig. 1. Moving image photographs of the flow established in the shock tube, M_I = 5.9

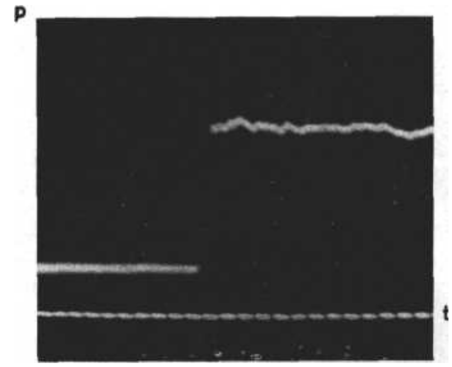

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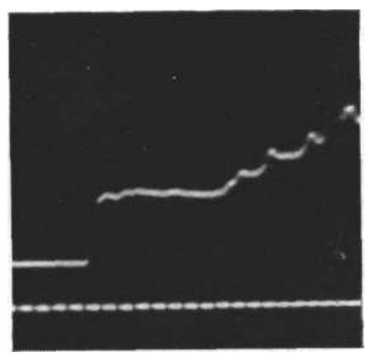
Fig. 2. Oscillogram of pressure behind the shock in inert gas



(a)

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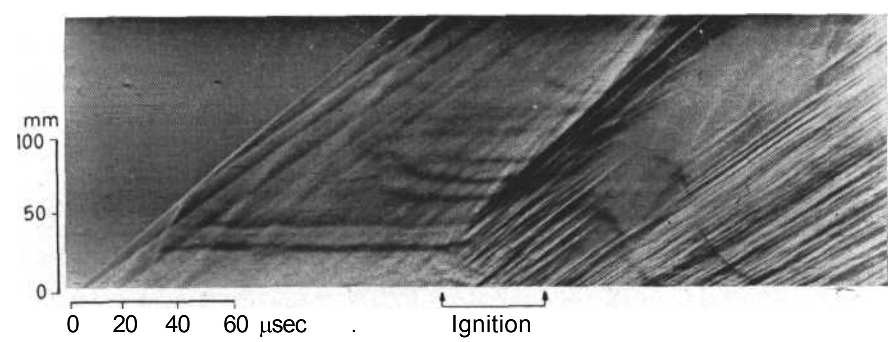


(b)

Fig. 3. Ignition initiation behind the shock wave in a mixture of natural gas and oxygen

It is pointed out that the final length of the sensitive surface of the pressure gauge (diameter 12 mm) considerably limited time resolution of the processes since these processes undergo considerable changes in the course of less than 5 μsec. The value of pressure registered during this interval was averaged.

According to our observations, the breaking of the diaphragm and a local temperature rise accompanying it did not lead to ignition of the mixture. This process with relatively weak waves took place much later than the moment of breaking the diaphragm, and developed in the end area of the heated gas. This area was usually located near the hot gas boundary, but in some cases the gas ignited at a great distance from the gas particles which had participated in the diaphragm rupture, thus the main experiments on ignition were carried out without a buffer section between the diaphragm and the mixture under test.

DEVELOPMENT OF THE IGNITION PROCESS OF GAS MIXTURES BEHIND THE SHOCK WAVE IN A CHANNEL HAVING A PERMANENT CROSS-SECTION

Figs. 3 to 5 show photographs of three experiments carried out under similar conditions. The section of observation was preceded by a 2 m section filled with a mixture of one part (vol) of natural gas and two parts of oxygen at a pressure of 0.06 kg/cm^2. The cellophane diaphragm was broken by hydrogen at a pressure of about 10 kg/cm^2.

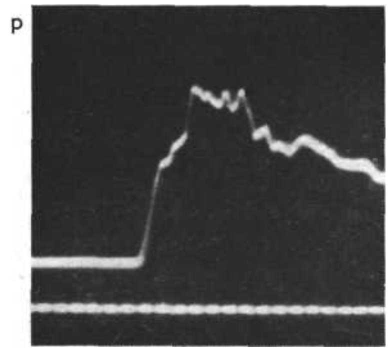
Because of the inevitable deviations, caused mainly by instability in the diaphragm rupture, the resultant shock waves differed from each other in intensity. As a result of this, different phases of the ignition process were reproduced on the photographs. Shock waves of a smaller intensity compared with the waves shown in Figs. 3 to 5 did not cause ignition while the pressure, measured by a piezo gauge in the front of these waves, was equal to the pressure, calculated on an assumption of a complete absence of chemical reactions. The density field behind the wave was uniform up to the contact surface.

Fig. 3a shows the initiation and progress of the gas ignition, also that in this case the gas ignition occurs with considerable delay (induction).

After breaking the diaphragm a flow, identical to the flow in inert gas, is initiated in the gas mixture. The shock wave is followed by a heated gas area of uniform density. In this case the pressure, measured by the oscillogram (to the right of the photograph) throughout this area behind the front, appears to be equal to the pressure behind the shock wave, which has been calculated by the shock wave speed on the assumption of a complete absence of chemical reaction. The relationship of the wave speed to the speed of the undisturbed gas sound is M_I = 4.2, which corresponds to a temperature of l,300 K behind the front. Examining the gas layers adjoining the contact surface it is possible to observe a density change which may be regarded as the beginning of gas combustion. The points of ignition noticeable by the aroused density disturbances, spring up immediately in the end area of the gas and spread together with the gas. The location of these points of combustion is shown by an arrow but the schlieren photographs do not make it possible to determine the location on the tube section. Perhaps they initially spring up in the gas layer adjoining the walls.

Fig. 6 shows several flash photographs. It is not difficult to see why the process is initiated in this way if we presume the existence of a final period of the mixture ignition induction. As a matter of fact, at high temperatures the layers of gas adjoining the contact surface are long-lived, it is in this area, therefore, that the combustion process can develop. Thus, after the 'latent' combustion phase, or the mixture pre-ignition phase, a regular combustion process is initiated. The points of ignition, springing up in the final gas volume, soon establish a boundary between burnt and unburnt gas, that is a flame front. The trace of the established flame front is also marked in the photograph by an arrow. The area of burnt gas of a uniform density can be seen between the flame front and the contact surface. The established flame front propagates in relation to the gas particles behind the shock wave at a subsonic speed. The relative speed of the flame front propagation in the first photograph is 345 m/ sec. As a result of the pressure exerted by the cold gas, the gas is burnt under conditions similar to the conditions of combustion in a constant volume. As a result a zone of burned gas having an increased pressure is formed near the contact surface. The resultant compression not only delays the cold gas movement behind the contact surface but also spreads after the shock wave, overtaking the flame front whose speed is subsonic.

These compression waves can be seen in Fig. 3a, but they are more clearly visible in Fig. 4. The compression waves propagation results in an additional temperature rise of the mixture before the flame front, which in its turn leads to an increased speed of this front. In Fig. 4 the flame-front speed in relation to the gas particles in front of the flame reaches 420 m/sec. Adding to the shock wave, the compression waves considerably increase its speed. In Fig. 4 the shock wave speed corresponds to M_I = 5.5, and the temperature behind its front reaches about 1,990 K. The pressure gauge registers the corresponding increase behind the shock wave front (see oscillogram in Fig. 4). In this case the schlieren photographs and the pressure readings show that the area between the shock wave and the flame front



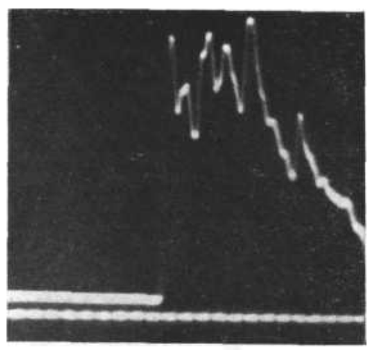
(a)

Marks 10 μ sec

(b)

0 20 40 60 **μsec** **Flame front**

Fig. 4. Flame front propagation in the gas behind the shock wave



(a)

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(b)

0. 20 A0 60 , **μ sec**

Fig. 5. Formation of detonation wave in a mixture of natural gas and oxygen

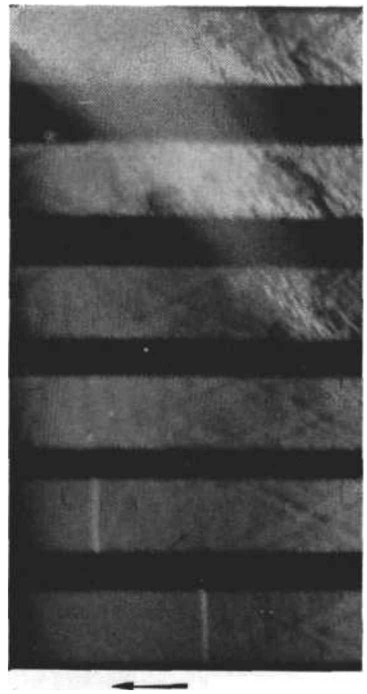


Fig. 6. Moving image photographs of the initial phase of ignition behind the shock wave. Photographs were taken at a rate of 40,000 shots per sec

ceases to be uniform because of the compression waves spreading from the combustion area. Under conditions of such a non-uniform and additionally heated area between the shock wave and the flame front, the final phase of the ignition process sets in explosion. This phase is well illustrated in Fig. 5. Since the reaction in the above mentioned area proceeds explosively the shock wave is sharply accelerated, immediately approaching the detonation speed. In this case a compression wave, usually called a retonation wave, spreads backwards through combustion products.

The pressure oscillogram shows that the final gas pressure in this phase of the process is several times more than the gas pressure behind the shock wave causing ignition.

In some cases the detonation front may be formed at a considerable distance from the front of the shock wave causing ignition. For example, Fig. 7 shows ignition of a mixture of 50 per cent of hydrogen and 50 per cent of air at the initial pressure of 0.1 kg/cm^2 at a distance of 2 m from the diaphragm.

The illustration shows that the mixture density begins to change at several points in the flow field behind the initiating shock wave ($M_I = 3.82$, $T_2 = 1{,}040$ K), and the width of these points slowly increases as they propagate behind the shock wave with the gas.

At a certain stage of this process a sharp increase in the expansion rate of one of the points takes place, and a detonation wave is immediately formed, which spreads in both directions at the same speed.

One of these detonation fronts will afterwards catch up withHhe shock wave front and merge with it.

Thus, merging of the flame front with the ignition shock wave is not a necessary condition of the detonation wave formation.

IGNITION OF GAS MIXTURES WITH GAS FLOW DELAYED IN THE ANGULAR STEP AREA

It is well known that if the intensity of a shock wave formed in gas capable of reactions is not sufficient to cause gas ignition behind the shock, the reaction may be initiated by a temperature rise caused by partial delay of the gas flow due to some obstacle behind the shock.

The shock wave propagating in the tube forms a boundary separating the motionless gas from the gas that has already been put in motion; therefore it is interesting to analyse the phenomena accompanying the gas current in the area of the contracting angular step and to compare the inert gas current with the current of gas capable of ignition.

Fig. 8 shows a series of flash photographs and the moving image of the air current formed by the shock wave interacting with the angular step. In the first the shock wave, moving from left to right, is located at some distance from the angular step having an angle of 40°. Density variations characterizing the supersonic flow are seen behind the shock. In the second the shock directly approaches the beginning of the channel contraction, but there are no changes in the gas flow as yet. No. 3 shows the flow turn near the step with new shocks of density springing up and a light area of rarefaction on the second bend of the channel profile. It is clear that the shock continues to spread along the narrow part of the channel.

From the left it is possible to conclude that the shock, resulting from the shock wave being reflected from the step, moves towards the gas flow and the rarefaction region extends (the rarefaction region boundary is reflected from the upper wall of the channel); then the nature of the flow is changed by the cold turbulized gas coming into view.

In Fig. 8b the inert gas flow process in the area of the channel angular contraction is shown. The horizontal slit was located along the centre of the chamber. In the step region a reflected wave is seen, propagating up the flow. A complex group of shocks and contact surfaces are spreading in the narrow part of the channel.

Fig. 9 shows a series of flash photographs and moving image of the combustible gas mixture flow in a channel with a concave angular step. In this experiment the intensity of the impinging shock wave was not sufficient to ignite gas in the flow behind the shock (T = 680 K). When the shock approaches the angular step a flow, identical to the above mentioned flow initiated at the turn of the flow in inert gas, is developed. In the shock, formed at the base of the step, an additional sharp temperature rise of the gas, already heated by the initial shock wave, is effected. Section 4 of Fig. 9a shows that in the flow behind the second shock, ignition accompanied by bright gas glow is initiated.

The ignition occurs in the delayed heated flow not at the moment of the sharp temperature rise after the shock but after a period of time, probably corresponding to the induction period of the given mixture in conditions, corresponding to the state of the gas behind the shock. The ignition front propagates up and down the flow at a constant speed approximating the speed of detonation.

The moving image of the process (Fig. 9b) makes it possible to follow more closely the development of the process in time. The initial phases of the flow reconstruction at the entrance to the contracting part of the channel proceed in the same way as in inert gas (Fig. 8b). In 50 sμec in the area behind the reflected shock it is possible to see the formation of two "diverging fronts, which are reproduced on the flash photographs by gas glow.

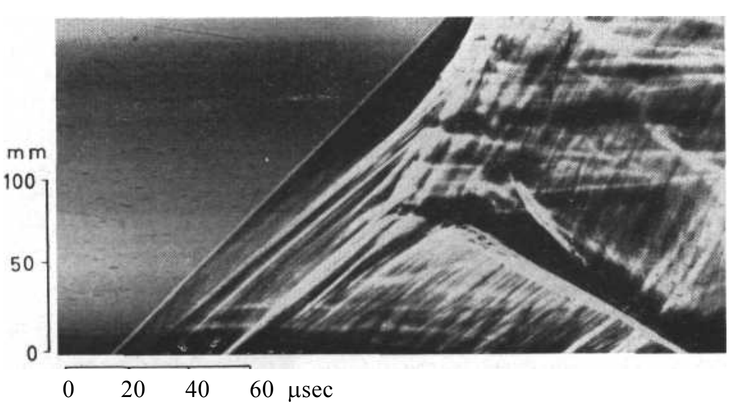


Fig. 7. Formation of a detonation wave in hydrogen-air mixture in the shock tube

(a)

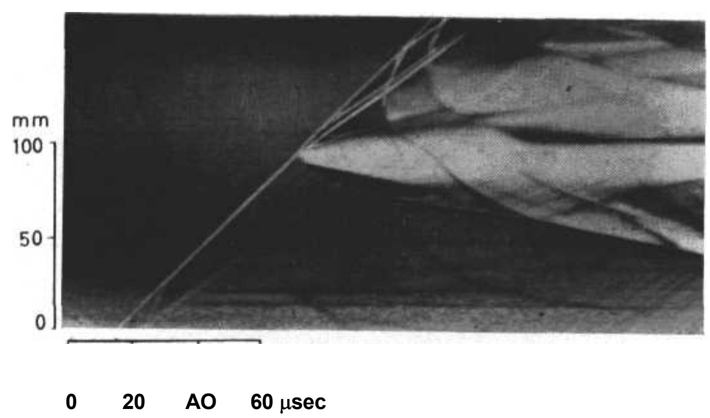


Fig. 8. Interaction of the shock front with the angular step in air

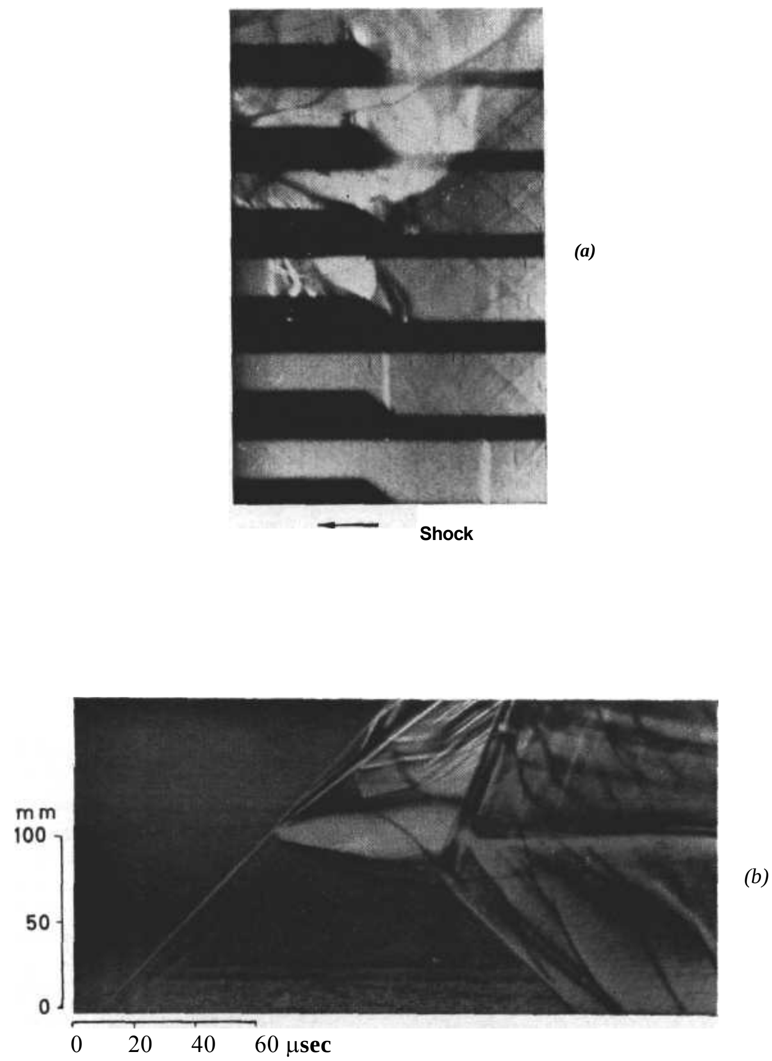
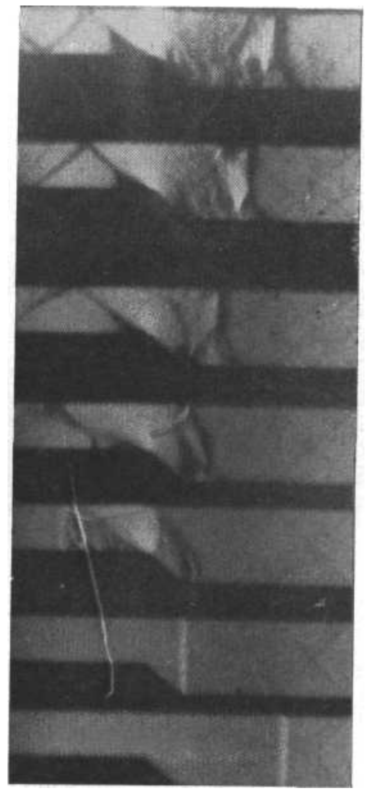
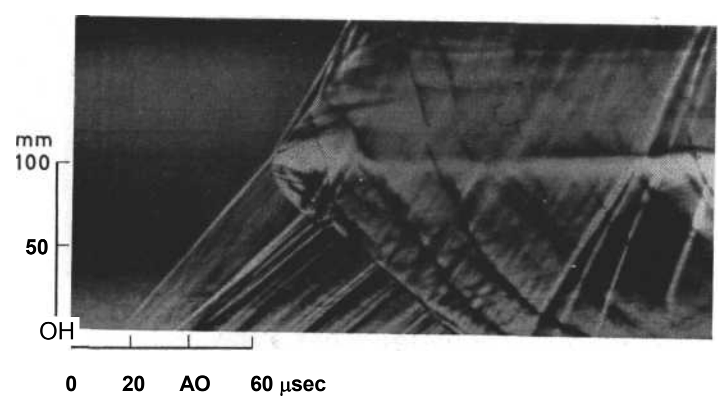


Fig. 9. Gas ignition in the angular step region with a noticeable delay



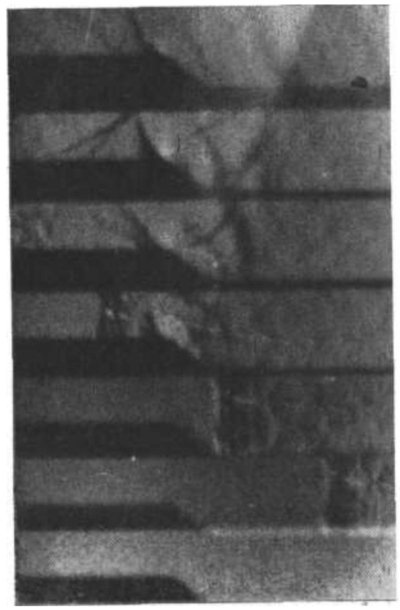
(a)

Shock



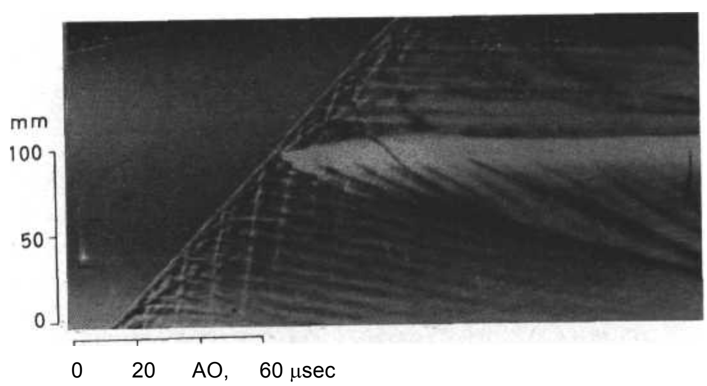
(b)

Fig. 10. Gas ignition in the angular step region
with a little delay



(a)

Det. wave



(b)

Fig. 11. Interaction of the detonation wave with the angular step

Fig. 10 shows interaction of the step with an impinging wave of greater intensity (T_2 = 790 K). As is seen from the photograph, by the moment of the interaction density non-uniformities occur in the gas behind the shock. We identify these non-uniformities with ignition points (Fig. 10a). In this case the detonation wave is formed immediately at the shock occurring near the step. At the same time the gas begins to glow (Fig. 10b).

Further increase in the impinging shock wave intensity results in the detonation being formed before interaction with the step. Our experiments have shown that in conditions of the shock tube a spin detonation is constantly initiated. Interaction of such a wave with the angular step is shown in Fig. 11. The spin structure is retained during the transition to the narrow section of the tube, and a reflected shock wave is formed in the reaction products in the same way as in inert gas.

Some estimates giving the conditions under which various gas mixtures are ignited in the shock tube are given in Table 1.

TABLE 1

No.	*Composition of*	*Initial* kg/cm^2	*Pressure behind the wave,* kg/cm^2	*Temperature behind the wave,* K	*Relay,* *μsec*	*Conditions observation*
1	Natural gas +$2O_2$	0-06	1-2	1,300	1,200	passing wave
2	$H_2 + O_2$	0-12	1-32	820	700	passing wave
3	$H_2 + O_2$	0-1	1-5	970	450	passing wave
4	air + H_2	0-1	1-65	1.040	1.100	passing wave
5	$4H_2 + O_2$	0-09	1-96	790	1,000	passing wave
6	$4H_2 + O_2$	0-09	0-74	680	50	at the step
7	$4H_2 + O_2$	0-09	0-96	790	0	at the step

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