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FAST DEFLAGRATIONS AND DETONATIONS
IN OBSTACLE-FILLED CHANNELS

Flames propagating in obstacle-filled channels are known to achieve very high speeds of propagation that can approach the speed of sound of the burnt products. The present paper reports the results of a detailed schlieren photographic study of such high speed flames. The experiments were carried out in two rectangular channels of different cross-section equipped with arrays of periodically spaced obstacles. The mechanisms responsible for the high speed propagation are identified as those which cause intense turbulization of the flame. These include shock-flame interaction, Raleigh-Taylor instabilities in an accelerating flow and autoignition in large recirculating eddies in the wake of obstacles. The transition from deflagration to detonation (DDT) in obstacle-filled channel as well as the structure and propagation mechanisms of quasi-detonations have also been studied. The results clearly identify the propagation mechanism of quasi-detonation to be one of autoignition by shock reflections. The obstacles play a dual role: a positive role of reinitiation by providing a surface for shock reflection and a negative role of attenuation by diffraction. On a global basis, obstacles have a negative effect on the overall average propagation velocity of the detonation.

INTRODUCTION

In the past decade there has developed considerable interest in the study of flames propagating in the turbulence field created by obstructing obstacles. The reason for the interest has to do with concerns related to safety. It has invariably been observed that if a combustible gas mixture is not too close to the flammability limits, than a flame propagating in an obstacle field can accelerate very rapidly to high supersonic velocities. Such high speed flames can drive shock waves with substantial overpressures. If the mixture is sufficiently sensitive, the highly accelerated flame may even undergo transition to detonation. Once established, the detonation wave then travels in the obstacle field at a steady velocity which can be significantly below the Chapman-Jouguet (CJ) level.

Substantial amount of research interest and activity has been generated by the accelerated flame phenomenon [1-11]. Considerable effort has been devoted to identifying the range of phenomenological behaviour of such flames and to deciphering the underlying mechanisms. Regimes of propagation have been classified and some attempts have been made to quantify limiting criteria responsible for the existence of the different regimes. From the practical point of view, the most important aspects of the accelerated flame phenomenon have to do with the steady-state propagation of very high speed flames, transition to detonation and propagation of sub-CJ detonations (quasi-detonations).

With regard to high speed flames it has been observed that a flame propagating in a continuous obstacle field will accelerate very rapidly and will reach a terminal, and on the average, the steady-state velocity, which it will then maintain for the rest of its passage over the obstacles. If the mixture is not too close to the flammability limits, the steady-state flame propagation velocity will approach the speed of sound of the combustion products. Extensive evidence now indicates that this level of flame velocity appears to be the maximum achievable by a turbulent flame in the non-detonative mode of combustion. Because of these observations it has been suggested that such maximum flame speed is prescribed and limited gas-dynamically by the process of frictional and thermal choking. Although this is a plausible explanation in the light of the observed behaviour, there has not been any more direct evidence. For example, it is not known whether it is the flame which drives itself to such high speed or that it is sustained by the precursor shock wave and wave interaction over the obstacles ahead of the flame.

The mechanisms underlying the propagation of sub-CJ detonations are also not understood at the present time. One school of thought suggests that it is the hot spots created by shock reflections at the obstacles that sustain the sub-CJ, detonation-like propagation, hence „quasi-detonations". The other point of view is that a steady-state CJ detonation is retarded by momentum losses in its propagation over the obstacles. However, the precise way in which this might occur is not understood.

The present paper attempts to address these problems by aiming to concentrate specifically on elucidating the mechanisms of propagation of fast flames and quasi-detonations. The relevant studies were performed by the author [12-14] with the use of high speed schlieren photography. Some of the results which will be presented in the next chapters were not published yet. Highly detailed photographic observations of the dynamics of the shock and flame fronts and their interactions with the obstacles yielded some insight underlying the mechanism of propagation of these combustion waves.

1. EXPERIMENTAL DETAILS

Two experimental apparatus used in these studies (Fig. 1) consisted of a long channel of rectangular cross-section. The channel itself was constructed by steel beams as the top and bottom walls, with metal plates (or optical quality glass panes) forming the side walls. The glass side walls provided a see--through capability for 1.2 m of the first apparatus, and for 60 cm of the second channel length (in its end part) to permit schlieren photography. The inner dimensions of the first channel were 61.8 mm high × 61.8 mm wide in cross--section by 1.5 m long. The inner dimensions of the second channel were 76 mm high x 16 mm wide in cross-section by 1.2 m long. The obstacle field was constructed of short lengths of 25.4 mm aluminium angle attached periodically at equal distance on a 6.4 mm thick aluminium backing plate. The channel of height 61.8 mm was filled with obstacles on one side only. The height d of unobstructed passage was always the same (i.e. d = 30 mm) giving the blockage ratio 0.5. Three spacing configurations were studied in the present experiments with L/d = 1.07, 2.14 and 4.28, where L is the inter-obstacle distance. In the second channel the obstacles were constructed of short lengths of aluminium flat bars attached periodically at equal distance on a 16 mm wide x 19 mm high aluminium bar. The bar therefore effectively reduced the vertical dimension of the channel to 57 mm. Once assembled, the obstacle array was slid into the channel along the lower steel wall and attached to it. After assembly, each obstacle was 16 mm wide, 1.6 mm thick and 25.4 mm or 12.7 mm high. The height d of the unobstructed passage is equal to 31.6 mm (for 25.4 mm high obstacles) or 44.3 mm (for 12.7 mm high obstacles). For the particular obstacle array, the inter obstacle distance L is constant. Three spacing configurations were studied in the experiments in the second channel with L/d = 0.8, 1.61 and 3.22.

In any given experiment, the channel was first evacuated to levels better than 0.01 torr. The apparatus was then filled to the predetermined initial pressure level from a high pressure reservoir containing the prepared stoichiometric H_2-O_2 mixture. The experiments were carried out at sub-atmospheric initial pressures in the range from 20 to 150 torr which was about the safe limit for the glass side walls of the present apparatus. Direct initiation of detonation in the mixture at one end of the channel was achieved in each experiment by a high voltage exploding wire using 100 μF capacitor charged to 4 kV.

Observation of the combustion phenomena was via high speed schlieren photography. The schlieren system was of the double-pass type and the main mirror delineating the field of view was a 30 cm diameter spherical mirror of high optical quality. The high speed camera used to record the events was a Barr and Stroud rotating mirror type. Through an array of 30 prisms, the

image of the event was projected on a stationary piece of 35 mm film, typically 75 cm long. This provided 30 frames of single-event photography. In the present study, the camera was run close to 500,000 frames per second which corresponds to about 2 μs between frames. The camera was illuminated from a linear xenon flash lamp (Xenon Corp. FPA 8100C). The duration of the illuminating flash was about 1 ms at half peak intensity level. Synchronization of events (ignition and illumination flash) was via two BNC Corp. Model 7010 digital delay generators. The initiation of events was manual followed by a pulse from a photo diode associated with the rotating mirror in the camera.
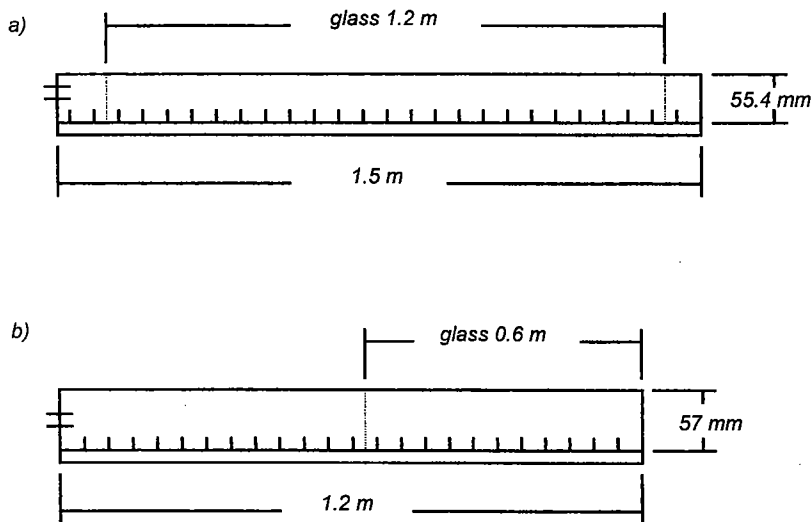

Fig. 1. Schematic diagram of experimental set-up: a) first channel; b) second channel

Velocity measurements were obtained by spacing a number of photo diodes (type TIL 78 N-P-N Silicon Photo transistor) along the glass side wall of the channel. The spacings of the photo diodes were at least 10 obstacles apart so the velocities reported were averaged values over a number of obstacles. Pressure measurements were obtained by calibrated fast response piezoelectric transducers (PCB 113A24, 5 mV/psi). Two transducers were used located at the top wall of the channel in its see-through section.

2. FAST DEFLAGRATIONS

The entire range of experimental results of the study in both channels can be summarized quantitatively in terms of the terminal steady-state velocity of

propagation of the high speed combustion waves over obstacles. This velocity information was deduced directly from the high speed schlieren photographs at the electronically monitored framing rate. Figure 2 shows the terminal velocity of the combustion wave as a function of initial pressure of stoichiometric hydrogen-oxygen mixture and for three different obstacle configurations in the first channel. Figure 3 shows the same phenomenon in the second channel. It should be pointed out that the flame speed as measured here is the sum of the burning velocity and the displacement velocity of the gas ahead of the flame. The flame propagation clearly falls into two distinct velocity regimes separated by abrupt jumps from one regime to the other at sharply defined mixture sensitivity boundaries for each obstacle spacing. In the present case the mixture sensitivity is determined by the initial pressure at a fixed composition. In previous studies [10,11,15,16], involving fuel-air mixtures at atmospheric composition, similar transition boundaries were also observed, but the mixture sensitivity was determined by the composition of the fuel-air mixture.
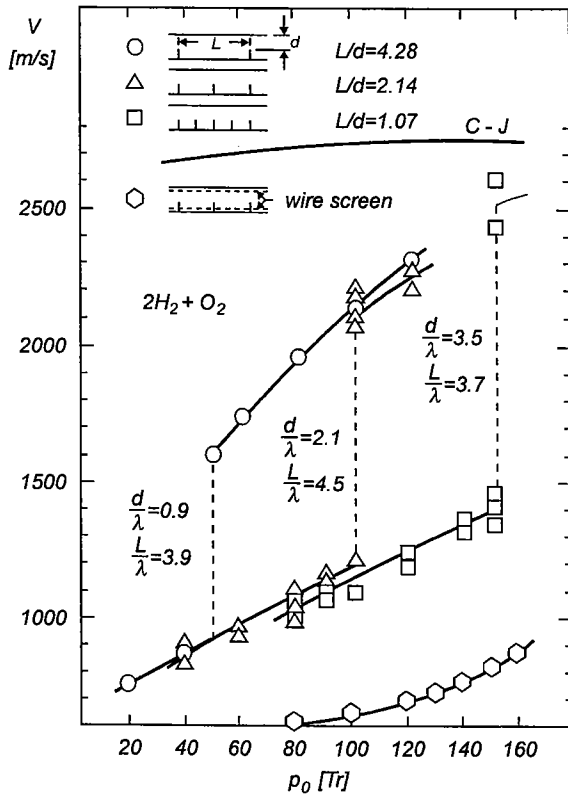

Fig. 2. Variation of terminal steady-state propagation velocity of combustion wave with mixture sensitivity (initial pressure) for $2H_2 + O_2$ mixture; first channel
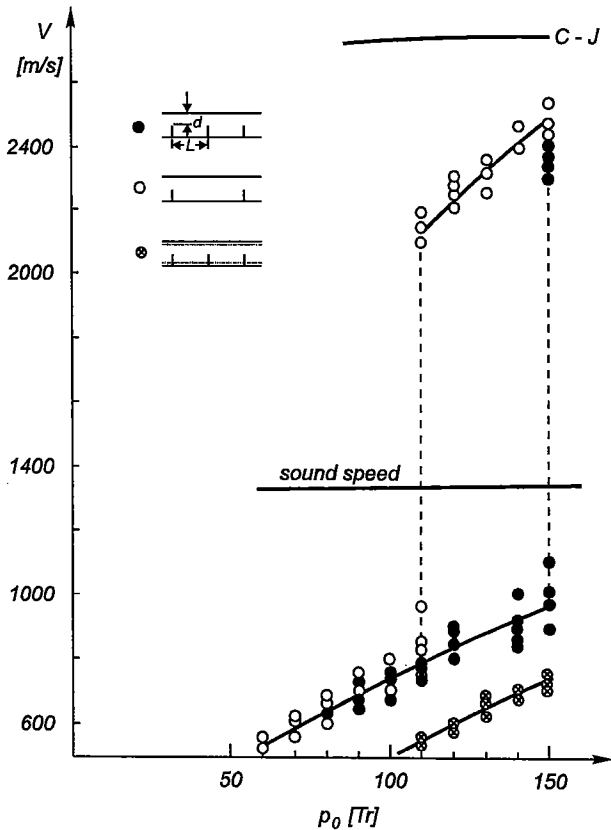
Fig. 3. Variation of terminal steady-state propagation velocity of combustion wave with mixture sensitivity (initial pressure) for $2H_2 + O_2$ mixture; second channel

The upper regime, the so-called quasi-detonation in which continuous periodic detonation failure due to diffraction by the obstacles and re-initiation by shock reflections constitutes the principal mechanism of propagation, will be discussed in detail in the next section.

The lower regime is the so-called fast deflagration regime (or the „choking" regime) in which a flame propagates with the velocity in the range of $600 \div 1000$ m/s which is close to the sonic speed of the burnt combustion products.

Figure 4 presents two different positions of the flame relative to the obstacle in the fast deflagration regime for the particular case of a relatively large spacing between obstacles ($L = 101.6$ mm) in the second (narrow) channel. The pictures clearly show the decoupled structure of the leading shock waves followed by a reaction front and both propagate with an averaged steady velocity of about 700 m/s. The leading shock wave is formed by the coalescence

of the pressure waves generated continuously in the violent turbulent flame brush. In the studies of flame propagation in smooth tubes by Meyer et al. [17], such precursor shock waves were also quite evident.
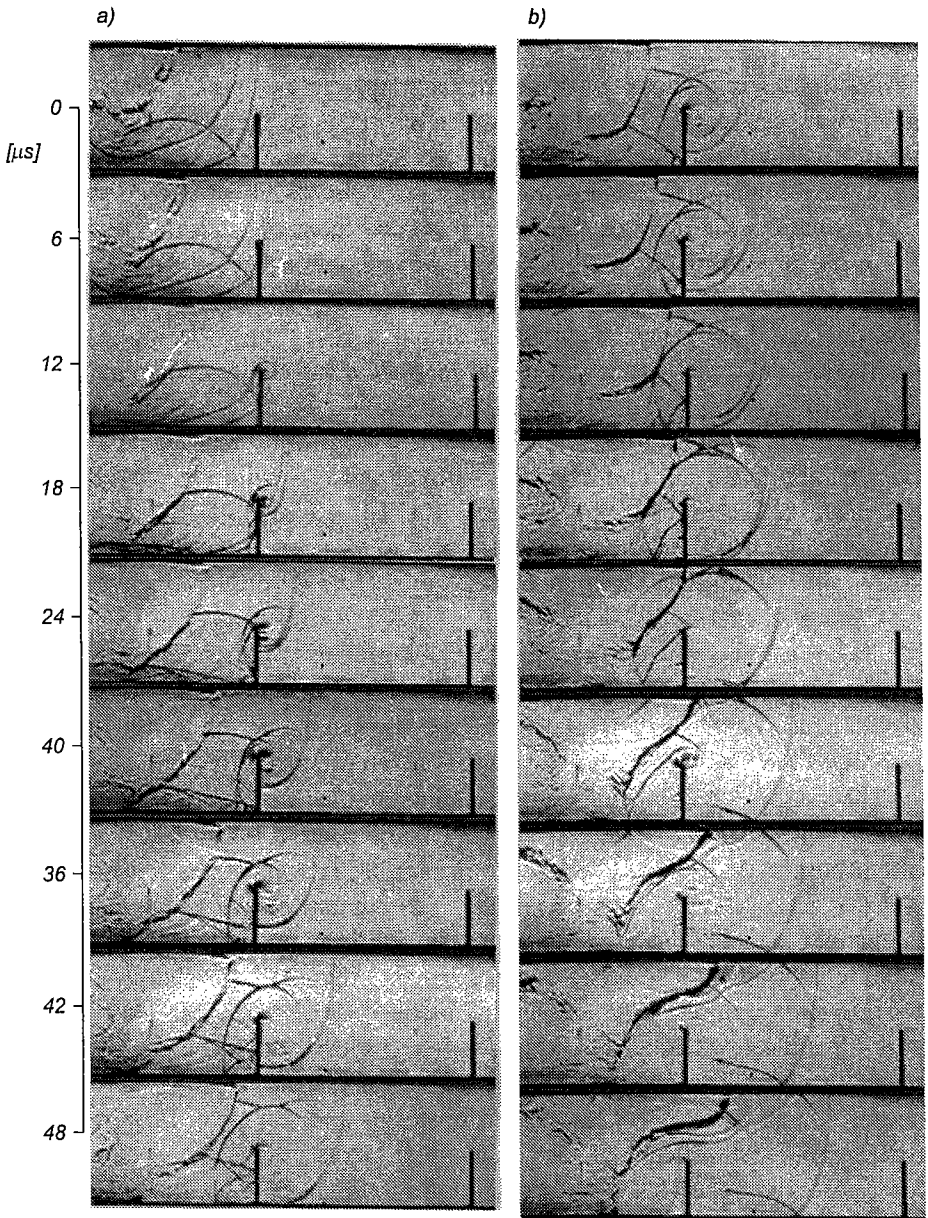

Fig. 4. Propagation of a high speed deflagration in obstacle filled channel (second) illustrating the stabilizing effect of the reflected shock interaction with the flame front (a), and the accelerating effect and the turbulization of the flame as it passes over an obstacle (b)

No ignition is observed behind the leading shock wave, since for this shock velocity the temperature behind the shock is only around 500 K. The leading shock wave, when it reflects from the bottom wall, first appears as a regular reflection and later on undergoes transition to a Mach reflection. Ignition does not occur behind either the regular reflected wave or in the Mach stem (in contrast to the quasi-detonation regime, as will be shown later). When the leading shock wave reaches an obstacle and partly reflects from it, again ignition is not observed in the region close to the obstacle. The reflection of the incident shock wave at the obstacle generates a cylindrical reflected shock wave which propagates transversely (upwards towards the top wall) as well as backwards towards the flame front and interacts with it.

In the frames of Fig. 4a the process of interaction between the shock wave (reflected from the bottom wall) and the flame is illustrated. It is clearly seen that the initial rough turbulent flame structure looks smoother after the shock interaction process. This is due to the Markstein instability effect which in this case is in the stabilizing direction (i.e. shock moves from high to low density fluid) so the flame perturbations are smoothened out. The process of flame stabilization is further continued by flame interaction with the curved cylindrical shock reflected from the obstacle which is clearly illustrated by Fig. 4b. The sudden change in the energy release rate associated with the shock wave-flame interaction also results in the generation of pressure waves, as was demonstrated first by Markstein [18].

The pressure waves when reflected from the top wall interact with the flame and now cause a destabilizing effect on the flame front. The flame is accelerated towards a denser medium and the growth of the perturbations thus turbulizes the flame front via Rayleigh-Markstein instability mechanism.

The detailed experimental investigation of Scarinci et al. [19] has shown that as a pressure wave passes through a flame front, a finite change in burning rate occurs at the flame. This change in burning rate generates a pressure pulse and the initial wave is thus amplified. The amount by which the burning rate is changed depends on the strength of the initial pressure wave as well as the mixture properties. The authors suggested that the change in burning rate may be correlated with the turbulent energy associated to Richtmyer-Meshkov instability. In these experiments, the dominant source of turbulence generation seemed to be the interaction of pressure waves (shocks) with density discontinuities (flame fronts). There were no obstacles and the mean flow was almost zero behind the reflected shock. Yet very intense turbulent combustion has been observed as well as high burning rates and high levels of pressure generation. It was suggested that the resulting turbulent combustion (behind the reflected shock) may be thought of as a collection of compressible burning vortices. Figure 5 which nicely illustrates this process comes from the latest fundamental studies of shock-flame interaction by Bombrey and Thomas [20].
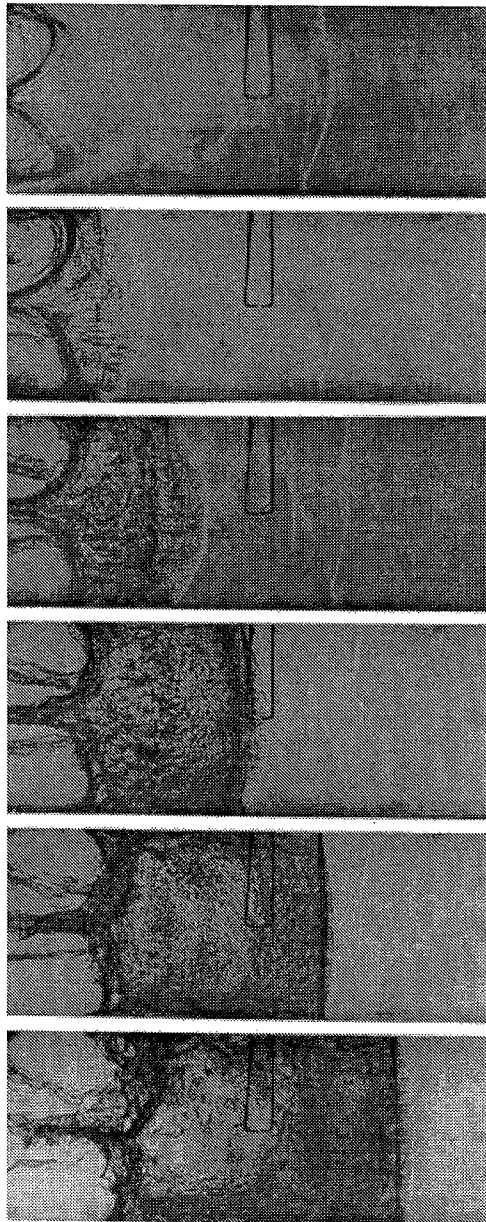
Fig. 5. Interaction of the flame front with the shock wave illustrating intense flame turbulization and the increase in burning speed (courtesy R.Bombrey and G.O.Thomas)

The last five frames of Fig. 4b show the flame propagation over the obstacle. Rapid acceleration of the flame and its turbulization are again clearly visible as the flame is convected along the accelerating converging flow past the obstacle. The similar character of flame propagation over the obstacle has
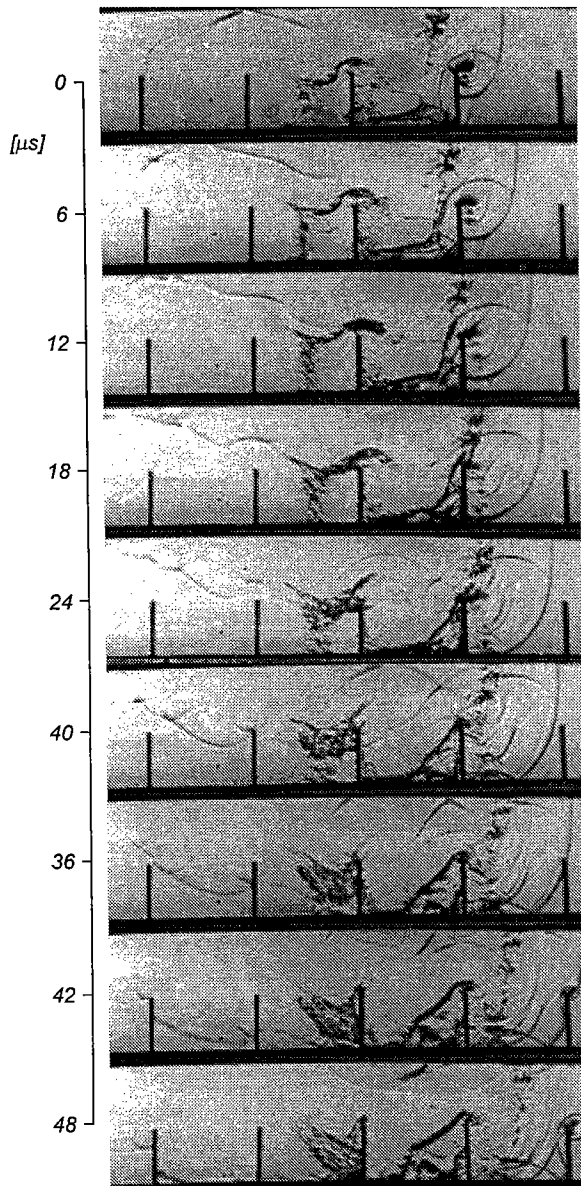
Fig. 6. Propagation of a high speed deflagration in a denser obstacle configuration (second channel) illustrating the accelerating effect of an exploding recirculation eddy

been observed experimentally in a single obstacle configuration by Wolański and Wójcicki [21] and by Tsuruda and Hirano [22]. According to Tsuruda and Hirano, the flame front turbulence is induced by the Taylor-Markstein instability mechanism and it is developed by the aerothermodynamical force acting near the curved flame front under acceleration (or pressure gradient).

Figure 6 presents a sequence of schlieren pictures of fast deflagration propagating with the average steady velocity of about 850 m/s in a denser obstacle configuration ($L = 50.8$ mm) and in more reactive mixture (initial pressure 140 torr). In this case the flame front moves closer to the leading shock wave. An incident shock wave diffracting over the obstacle forms in its wake a large recirculation eddy. In this recirculation zone unburned mixture is mixed with combustion products entrained from the flame zone above the shear layer as the flame propagates past the obstacle on the top half of the channel. This recirculation eddy after some ignition delay time auto-explodes, generating pressure waves which interact with the flame causing its further acceleration and turbulization.

Figure 7a presents the sequence of schlieren pictures of a fast deflagration in a very dense obstacle configuration ($L = 25.4$ mm) in the second channel. A very complex wave interaction pattern is observed which results from the periodic shock diffraction and reflection from the obstacles and the walls, inter shock reflections and explosions of eddies behind the flame front. This complex wave structure causes intensive flame turbulization which provides the mechanism for the very high speed of propagation of the shock-flame complex equal to about 1200 m/s in this particular case (close to the sound speed of the combustion products).

To demonstrate the role of transverse waves on the propagation of fast deflagrations, layers of fine wire screens were placed both on the bottom and the top wall of the channel to damp out these waves. The wire screens have been shown previously to effectively damp out shock reflections [23]. It was found that placement of the wire screens decreased the propagation velocity of fast deflagrations by about $200 \div 300$ m/s in the same obstacle field and mixture sensitivity (Fig. 2 and 3). This indicates that the elimination of the transverse waves also partly eliminates one of the mechanisms for the turbulization of the flame via shock-flame interaction. The structure of the deflagration with the wire screens placed on the top and the bottom walls of the channel is shown in Fig. 7b. Comparing with Fig. 7a where the obstacle configuration is identical, one notes that the transverse waves are greatly suppressed. The flame front also takes on a more planar structure when there is strong interaction with the transverse waves.

Extensive studies of fast deflagrations in very rough tubes in the past decade [2,10,11,15,16] have shown that the velocity of their propagation can range from 500 m/s to 1000 m/s. In general these propagation velocities are dependent on the turbulent transport rates, and thus the detailed flow structure. Because of the complexity associated with their highly turbulent structure, it has been extremely difficult to analyze and predict such high speed deflagrations.
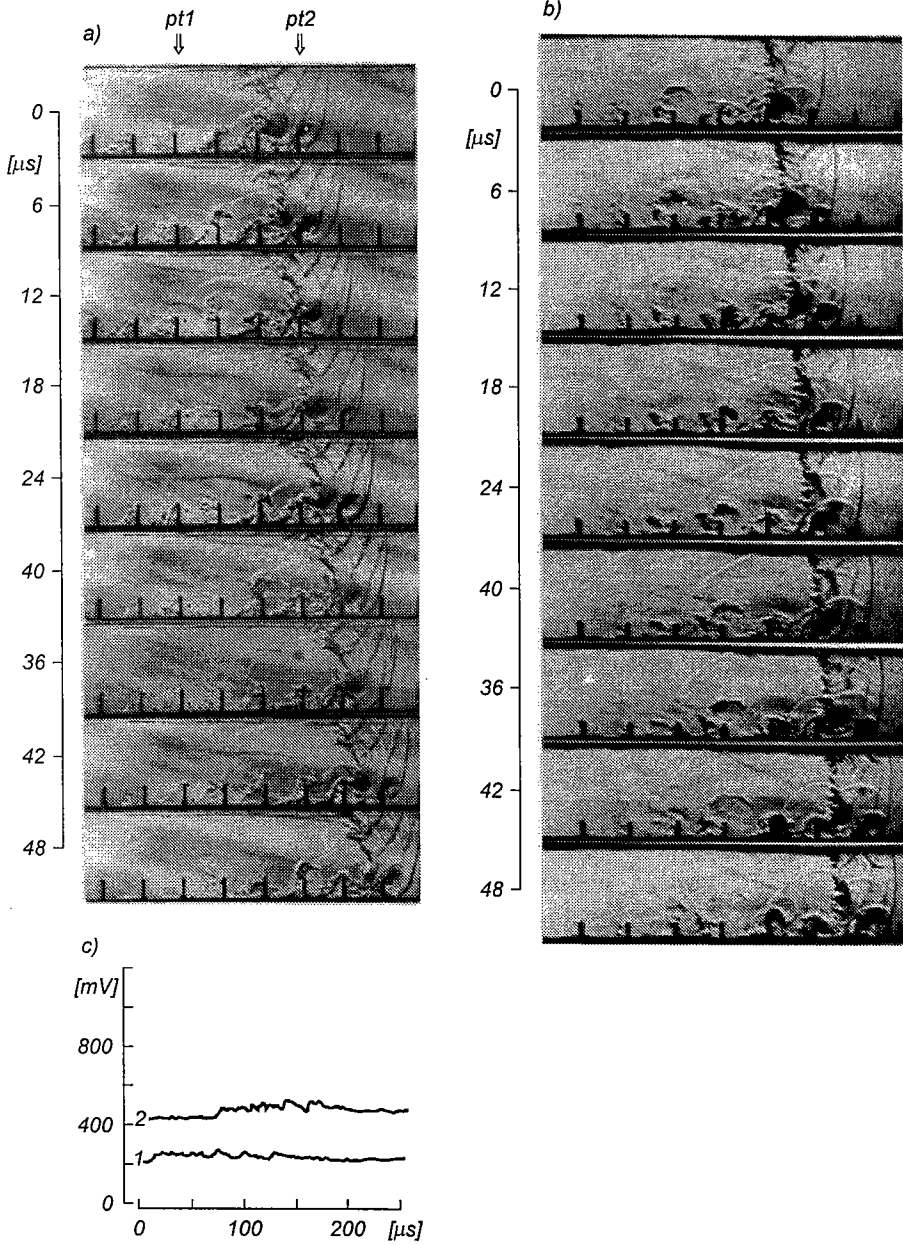
Fig. 7. Propagation of a high speed deflagration in a densely packed obstacle field in the second channel illustrating the consequent intense turbulization of the flame (a), and the attenuating effect of side mounted wire screens (b)
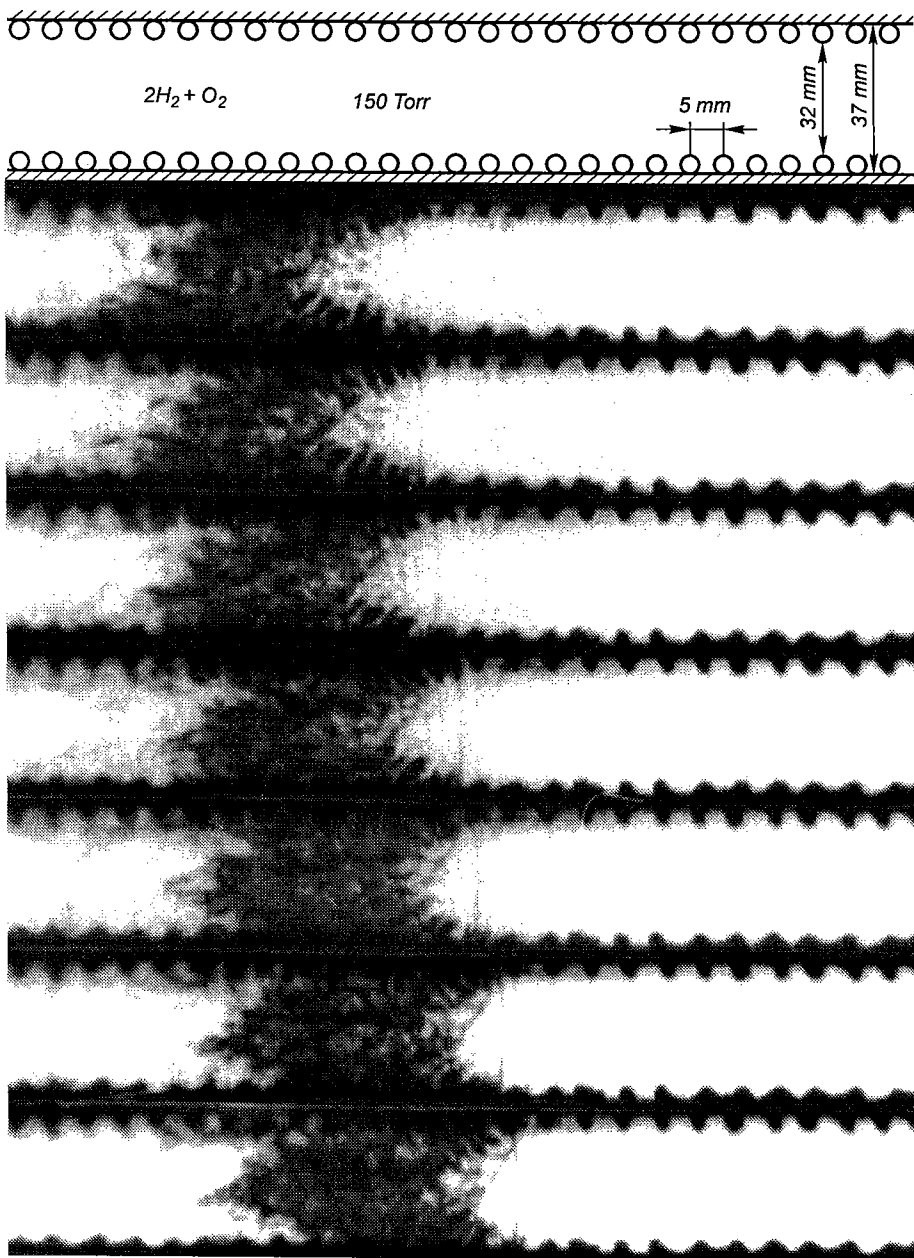
Fig. 8. Time sequence of schlieren photographs illustrating the complex structure of the propagation of a turbulent high speed deflagration in a very rough channel; stoichiometric H_2-O_2 mixture at 150 torr

The flow structure of a turbulent high speed deflagration is illustrated in Fig. 8, which is a time sequence of high-speed framing schlieren photographs of such propagation for a stoichiometric hydrogen-oxygen mixture in the second channel where the large roughness of the top and bottom walls is modelled by small cylindrical obstacles 2.5 mm in diameter. The structure can be seen to consist of a series of compression waves in the front, followed by a highly turbulent reaction zone. The leading compression waves are not strong enough to cause autoignition so that the trailing reaction zone propagates with the characteristic V-shape with the leading edges at the wall where intense turbulence is generated by the wall roughness as well as shock reflections on the obstacles take place. The shock-flame complex which propagates with the velocity about 1000 m/s is only 40 cm apart the weak (~1 mJ) electric spark ignitor.

Figure 9 shows the same mixture in the same channel configuration, however layers of fine wire mesh were put on the walls beneath the obstacles to damp the transverse pressure waves. The propagation velocity of the flame at the same position of the channel is reduced in this case to 100 m/s and no compression waves are visible. Thus the importance of the transverse waves in the fast deflagration regime is evident.

In the experimental study by Dupre et al. [23] it was found that when the transverse waves of a steadily propagating multi-headed detonation are damped out by an acoustic absorbing wall, a fast deflagration is obtained. The similar experiments were performed by the author with the use of schlieren visualization [24] in order to examine the structure of the combustion wave. The high-speed framing photographs of the propagation of detonation wave over the fiber glass damping section are shown in Fig. 10. The strip of fiber glass used was 24.4 mm thick and 150 mm long. In the early frames on the left one can see the planar detonation wave with horizontal striations behind it indicating the tail ends of the transverse waves. As the wave encounters the compliant wall the horizontal striations begin to disappear progressively so that by frame twelve they are completely absent and the decoupling of the shock and the reaction zone is seen to begin. On the right sequence the wave becomes completely and progressively more decoupled in the later stages of propagation over the compliant wall segment. The shock-flame complex propagates at about half the CJ detonation velocity. Whether the decoupled shock and reaction front transits back to a regular cellular detonation afterwards will depend on the wall roughness of the tube downstream of the damping section.

In the recent paper of Chue et al. [25] the very fast deflagrations shown in Figs. 8 and 10 were analysed with the use of simple one-dimensional model as a CJ deflagrations. The analytical solution obtained for constant specific heat ratio and large heat release demonstrates that the propagation velocity of
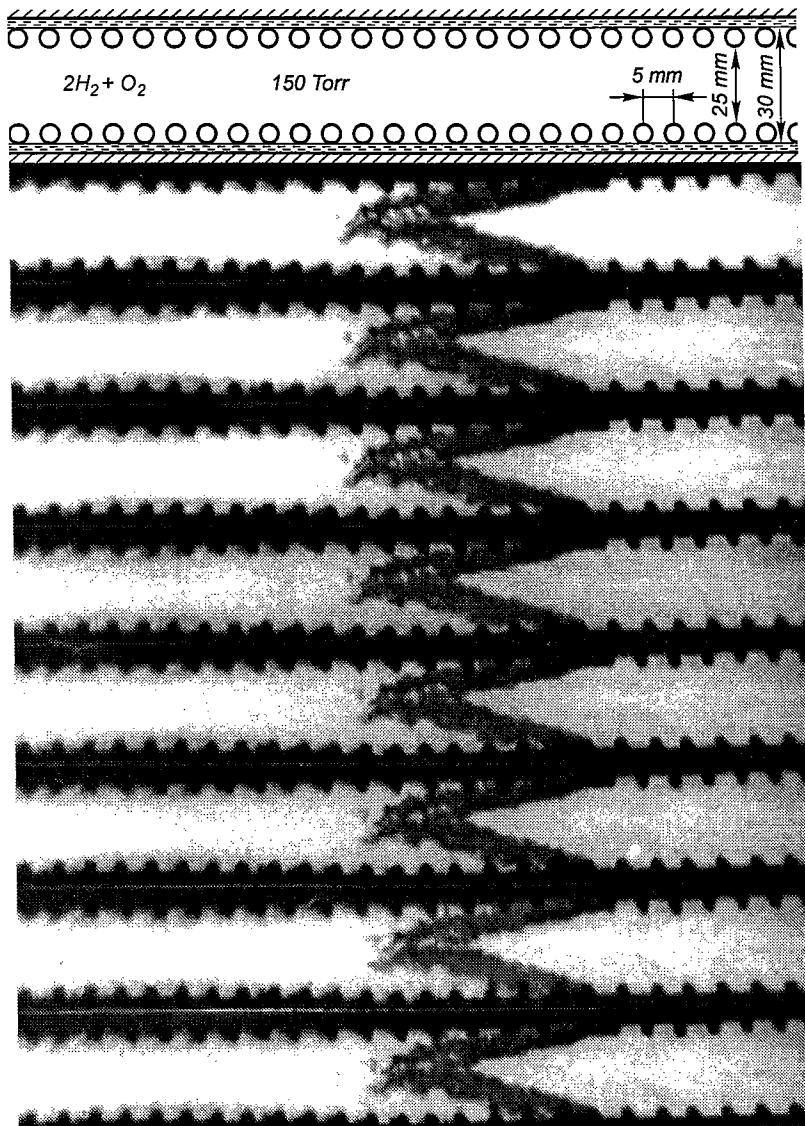
Fig. 9. Propagation of a high speed deflagration in very rough channel with side mounted wire screens

these fast deflagrations are close to one half the propagation velocity for CJ detonation corresponding to the same mixture, as have been shown in the experiments. It was finally concluded that these maximum velocity deflagrations propagate at the sound speed of the product gases. They are energetics governed and are independent of the detailed flow structure.
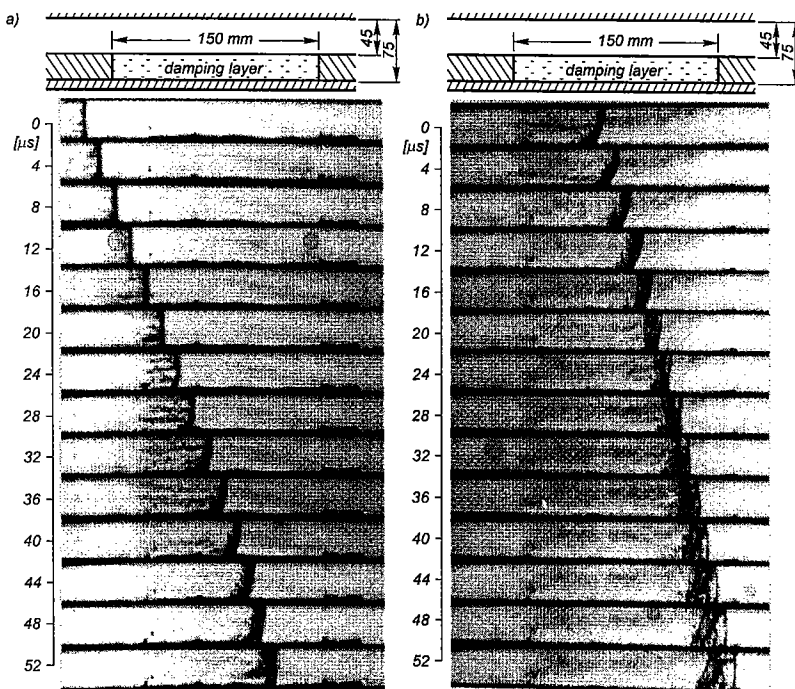
Fig. 10. Two time sequences of schlieren photographs illustrating the damping of transverse waves of an established detonation by an acoustically absorbing wall; stoichiometric H_2-O_2 mixture at 120 torr; first channel, 61.8 mm wide

3. TRANSITION FROM DEFLAGRATION TO DETONATION (DDT)

Detonation wave can be generated instantaneously via direct initiation if a sufficiently powerful ignitor is used. If a weaker ignitor is used, a deflagration wave is obtained. Under the appropriate conditions (e.g. confinement and roughness of tube walls) a deflagration will accelerate and undergo an abrupt transition to a detonation wave. This mode of initiation is referred to as the transition from deflagration to detonation (or DDT).

Most of the studies on DDT were carried out in long smooth tubes. The propagation of deflagration and detonation in confined tubes are very complex phenomena in which the initial and boundary conditions play dominant roles.

In the case of the unconfined or spherical geometry only for extremely sensitive fuel-oxygen mixtures (e.g. C_2H_2-O_2) the transition from spherical deflagration to detonation has been observed experimentally. For fuel-air mixtures DDT has not been observed even for sensitive fuels such as C_2H_2 and H_2 for the purely unconfined geometry. This may be due to the very large

scale required for the deflagration to accelerate to DDT in fuel-air mixtures. However, there may also be a fundamental limitation on the inability to generate strong enough large scale turbulence in the spherically diverging unburned gas flow in the absence of shear due to solid boundaries for the purely unconfined geometry.

In confined tubes DDT can readily be observed even in fuel-air mixtures. A distinction should be made between DDT in smooth and rough tubes since wall roughness plays a very strong part in both the propagation of deflagration and detonation. In recent years many studies have been carried out in very rough tubes referred to as obstacle filled tubes [10,11,15]. In smooth tubes, the onset of detonation is marked by an abrupt change in the propagation speeds. Typically, pre-detonation flame velocity is less than 1000 m/s and the CJ detonation speed is over 2000 m/s. A very strong local explosion always occurs at the onset of detonation so that the detonation wave formed is highly overdriven initially and decays subsequently to its CJ value. The shock wave from this local explosion that propagates back into the combustion product gases is referred to as the retonation wave. Detailed schlieren photography of the onset of detonation processes obtained by Urtiew and Oppenheim [26] revealed that the local explosion usually occurs at the turbulent flame brush. Detailed calculations performed by Meyer et al. [17] also indicate that shock heating cannot account for the auto-explosion and they suggested the importance of auto-ignition induced by turbulent mixing in the flame zone.

For very rough tubes the flame acceleration is much more rapid as it was shown in previous section. Transition to detonation is also not so clearly marked by an abrupt explosion. Quite often, an almost continuous acceleration to the final steady-state propagation speed is observed. The presence of very rough walls (or repeatable obstacles) permits steady-state flame speeds continue over the entire range from slow deflagration to CJ detonation. The wall roughness controls the propagation of the wave by providing [27]:

(a)   means for generating strong large-scale turbulence, thus a larger fraction of the mean   flow kinetic energy can be randomised;

(b)   means for generating strong shock reflections and diffractions and thus an additional mechanism for the randomisation of the mean flow energy via these complex wave interaction processes;

(c)   means for generating high local temperatures for autoignition via shock reflections (normal and Mach) which otherwise is not possible by the incident shock themselves (without reflections).

Lee and Shepherd [27] concluded from the experimental observations that in the complete absence of boundaries for shear and wave generation, as in a pure spherical geometry, the flame through its own self-turbulization mechanism of instability cannot provide sufficient randomisation of the mean flow kinetic energy to cause DDT except in extremely sensitive mixtures. With very rough-walled tubes, the obstacles provide an efficient means of flow randomisation through large-scale turbulence and wave reflections leading to DDT much sooner than in smooth tubes.

Figure 11 shows two unique time sequences of schlieren photographs of DDT in very rough channel made by the author. It is clearly seen that, as in
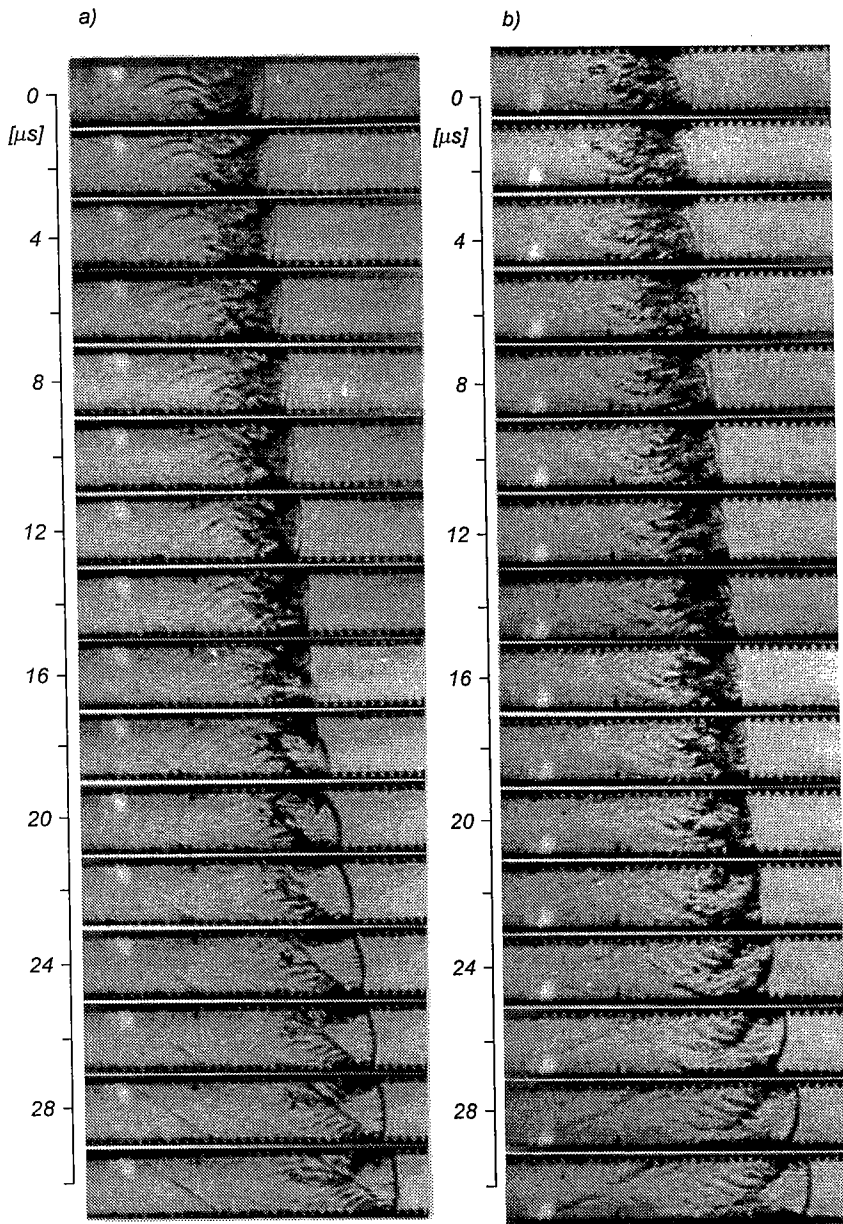

Fig. 11. Two time sequences of schlieren photographs showing transition from deflagration to detonation in very rough tube; stoichiometric H_2-O_2 mixture at 100 torr

the smooth tubes, the transition to detonation is associated with the sharp change in the propagation velocity. Fast deflagration immediately before DDT

propagates with the speed 1400 m/s, however after transition the detonation velocity is equal to 3000 m/s. In contrast to smooth tubes in this case turbulent flame fully overcomes the leading shock wave at the moment of transition to detonation. The onset of detonation is probably caused by the explosion at the thick flame brush. Surprisingly no retonation wave is observed in schlieren pictures. By no means further studies of this process are necessary.

4. QUASI-DETONATIONS

The propagation of detonation in very rough tubes has been studied by numerous authors, starting with the pioneering works of Lafitte [28], Shchelkin [29] and Guenoche and Manson [30]. Steady detonation velocities as low as 40% of the normal CJ value have been observed. Such low velocity detonations have been referred to as quasi-detonations [31]. Heat losses to the walls are not sufficiently rapid to account for such large velocity deficit since $D_{CJ} \sim \sqrt{Q}$ according to equilibrium one-dimensional theory. Thus, 50% velocity deficit would require a fourfold reduction in the effective energy release.

Figures 2 and 3 show the quasi-detonation velocity as a function of initial pressure for the stoichiometric H_2-O_2 mixture in two experimental channels studied. The quasi-detonation velocity ranges from about 50% to the normal CJ velocity depending on the mixture sensitivity (i.e. initial pressure) and obstacle spacing. It is evident that transition to detonation occurs when both characteristic dimensions d and L accommodate several detonation cell sizes λ. Comparison of the results from wide (Fig. 2) and narrow channel (Fig. 3) shows that, for similar values of d/λ and L/λ, the quasi-detonation as well as deflagration velocities are lower in the narrow channel. This indicates the three-dimensional nature of the quasi-detonation and fast deflagration processes, which is also reflected in the propagation velocity of the wave itself. That is, the added dimension provides for transverse wave collisions and reinitiation to offset the attenuating effect of the obstacles.

It was found in both experimental channels that the approach to the normal CJ detonation velocity occurs when $d/\lambda \approx 5$. Since the apparatus is essentially a half channel (i.e. the top wall being the axis of symmetry) the results indicate that the approach to CJ velocity would occur when $d/\lambda \approx 10$ for a full channel. This observation is in accord with the critical tube diameter criterion [32-34] which states that $d/\lambda \geq 10$ for successful transmission of detonation through square channels. Thus, diffraction of the detonation past the obstacle causes the wave to fail for $d/\lambda \leq 5$ (for half channel). The two sequences of framing schlieren photographs in Fig. 12, showing a detonation wave propagating into an obstacle array, clearly illustrate critical tube criteri-
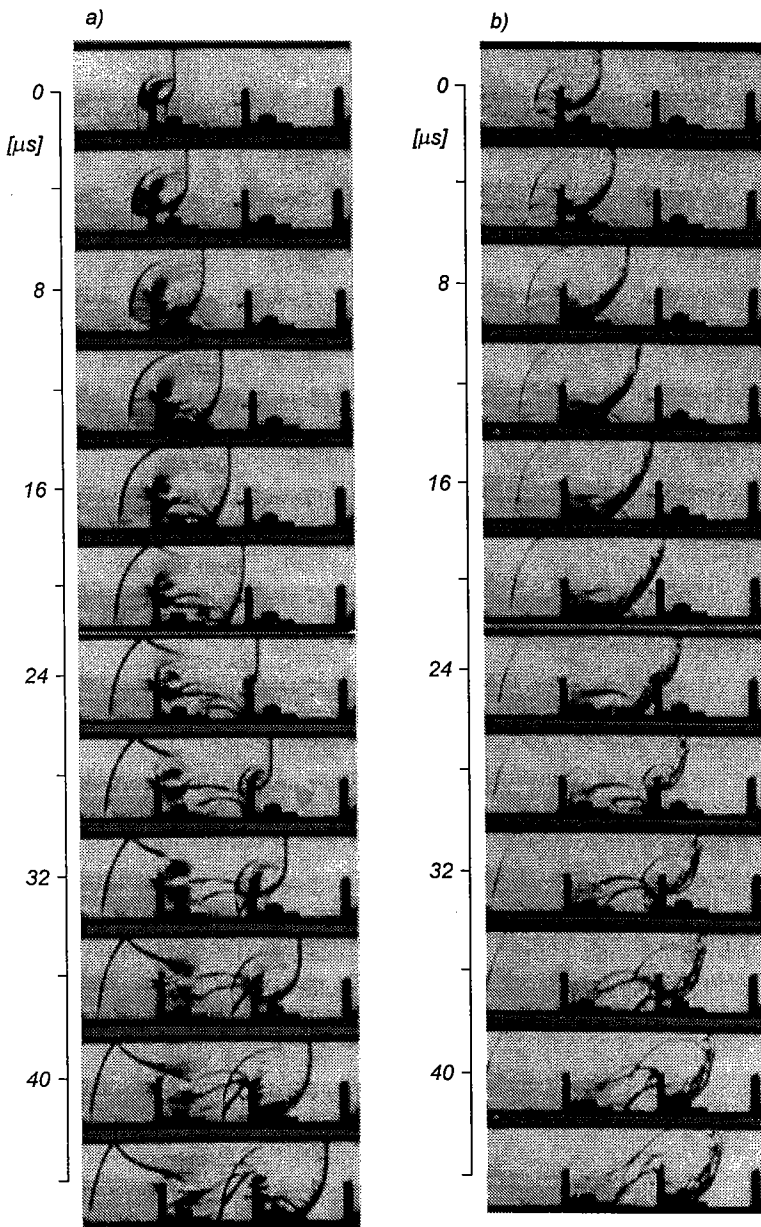
Fig. 12. Propagation of detonation over an obstacle array in $2C_2H_2+5O_2$ mixture: a) initial pressure — 60 torr, $d/\lambda = 15$; b) initial pressure — 20 torr, $d/\lambda = 3.8$

on. In the case where $d/\lambda > 5$ (Fig. 12a), the detonation at the top wall always remains normal to the wall, while the diffracted wave over the obstacle fails with a thickening of the reaction zone due to the expansion waves. The sequence shown in Fig. 12b illustrates the failure of detonation to self-reini-

tiate near the top wall since $d/\lambda < 5$. Decoupling of the reaction zone from the shock and significant curvature over the entire leading shock front are clearly visible.

In general, the obstacles and walls (top and bottom walls in the present case of a two-dimensional geometry) provide surfaces for the reflection and diffraction of shock and detonation waves. Figure 13a shows a sequence of
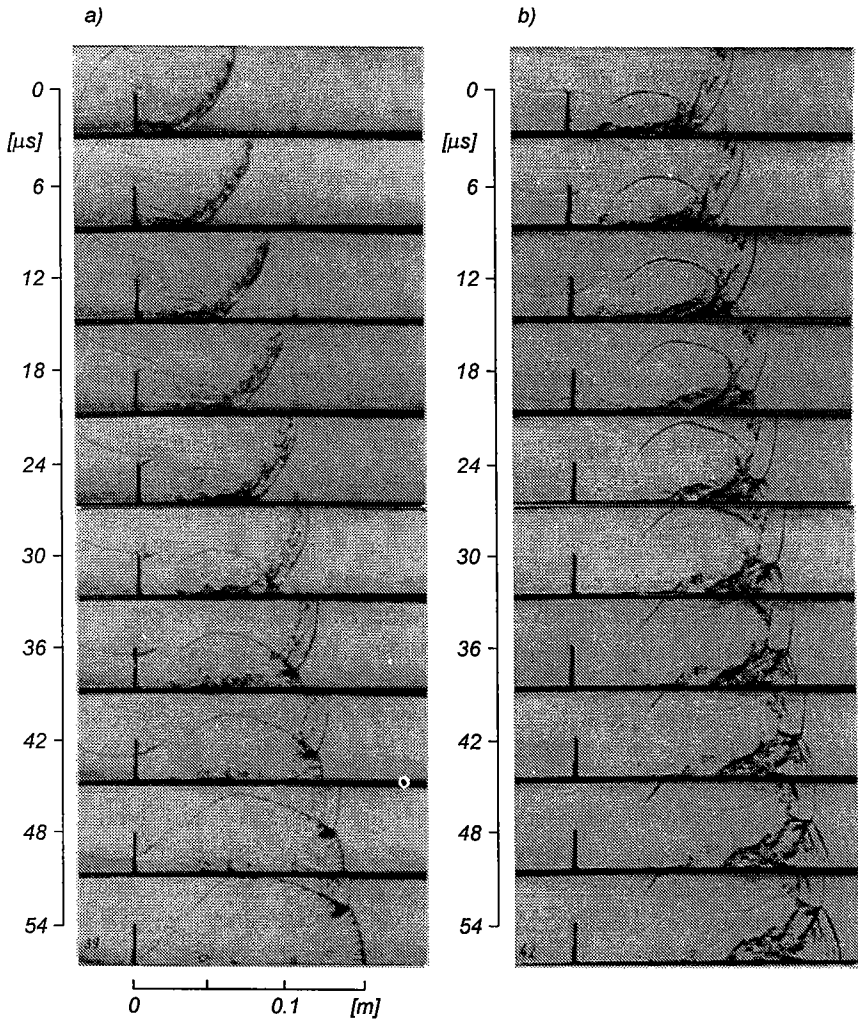

Fig. 13. Interaction of detonation wave with single obstacle in $2H_2 + O_2$ mixture: a) initial pressure — 140 torr, detonation reinitiation in Mach reflection zone at bottom wall; b) initial pressure — 90 torr, no detonation reinitiation

schlieren photographs when a normal detonation wave encounters a single barrier. The first frame clearly shows the reflected shocks in the combustion products, the transmitted and diffracted leading detonation front in which the

reaction zone is decoupled from the shock and the normal reflection of the diffracted shock just begins on the bottom wall. The decoupled shock-reaction zone complex decays continuously and its velocity decreases from about 2000 m/s at the second frame to about 1200 m/s at the last frame. In the sixth frame of Fig. 13a the transition from regular to Mach reflection occurs. Since the Mach stem is sufficiently strong, autoignition and reinitiation to a multi-headed cellular detonation occurs there. The reinitiated Mach stem propagates at the speed about 2400 m/s, which corresponds to self-sustained detonation with its characteristic fine cellular structure. The decoupled deflagration near the top wall continues to attenuate with the reaction zone now completely separated from the leading shock front as the reinitiated cellular detonation from the bottom wall sweeps upward. Without further encounters with another obstruction, a multiheaded cellular wave then continues to propagate along the channel. If, however, another obstacle is encountered, the detonation will dif-fract around it and the expansion waves will cause the detonation to fail. The reinitiation process then repeats itself. Figure 13a shows one reinitiation mech-anism that is possible when the Mach reflection of the diffracted shock from the bottom wall is sufficiently strong for autoignition. In Fig. 13b the condi-tions are such that the Mach stem is not strong enough to cause reinitiation (leading shock propagates here with velocity about 1000 m/s). The turbulence in the shear layer and the wall jet associated with the triple point cause intense combustion activity in the region of the reflected shock. However, the Mach stem is clearly a shock front and the reaction zone is not coupled to it as com-pared with the previous case shown in Fig. 13a.

In Fig. 14 the effect of obstacle spacing is demonstrated clearly. As in the previous case shown in Fig. 13a, reinitiation occurs at the Mach stem on the bottom wall. However, prior to complete reinitiation of the decoupled wave by the upward-growing detonation, reflection and, subsequently, diffraction of the detonation occur again by encountering another obstacle. In the sixth frame of Fig. 14a, the curved, diffracted, and reflected shock with a reaction zone close behind is clearly evident. However, as this cylindrical deflagration expands, progressive decoupling of the reaction zone occurs. In the last frame, this en-tire shock and reaction zone complex is decoupled. The destructive role played by obstacles in causing the failure of detonation is now clear. With higher obstacle density (i.e. more obstacles per unit length), more frequent attenuations by diffraction of the reinitiated detonation occur. This explains the decrease in the „averaged" velocity of quasi-detonations with increasing obstacle density reported previously [35].

As shown in Fig. 13b, the Mach stem at the bottom wall fails to cause reinitiation, and the reaction zone is not coupled to it. However, when this Mach stem encounters another obstacle, the normal reflection of the Mach stem from the front of the obstacle then may cause reinitiation. Figure 14b shows such a reflected Mach stem reinitiation. The part of the initiated deto-nation that transmits through the reaction zone now propagates into the com-
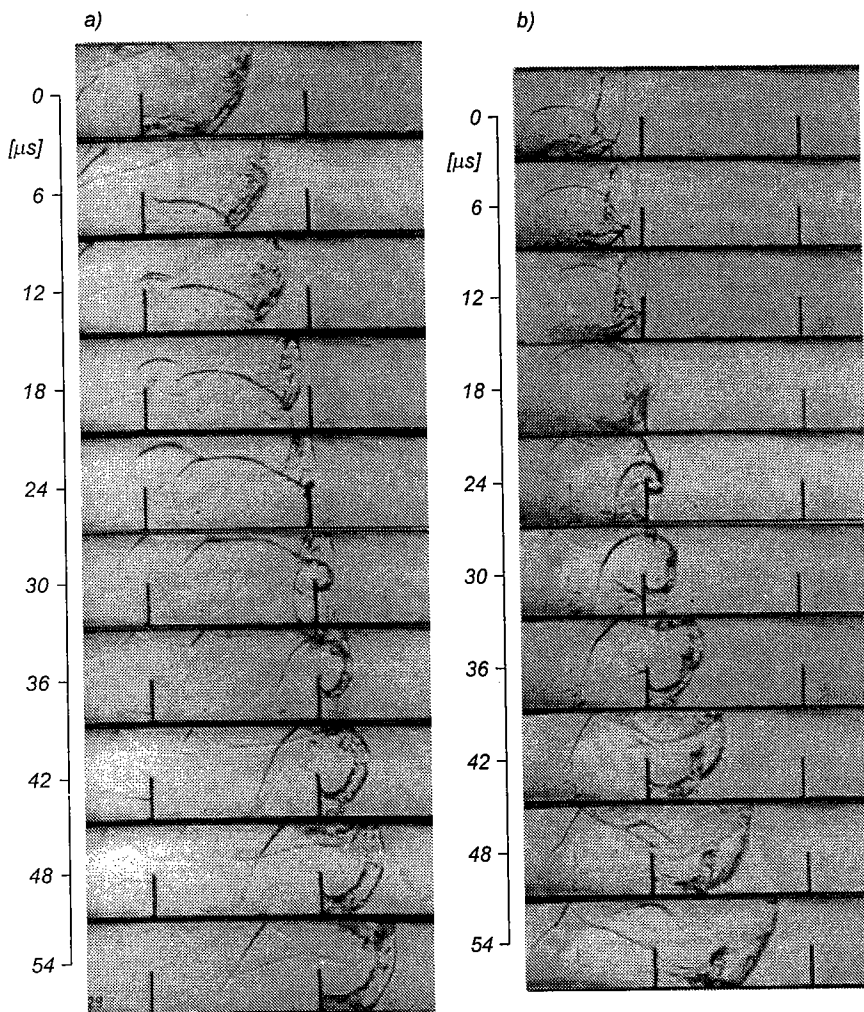
Fig. 14. Propagation of quasi-detonation in obstacle array in $2H_2 + O_2$ mixture: a) initial pressure — 140 torr, detonation reinitiation in Mach reflection zone at bottom wall; b) initial pressure — 120 torr, detonation reinitiation by normal Mach stem reflection from the obstacle with subsequent enhancement via reflection from top wall

bustion products, thus it becomes a shock. However, the part of the detonation that diffracts around the obstacle and propagates in the unburned mixture between the leading shock front and the reaction zone develops into a cylindrical detonation. However, as shown in the sixth and seventh frames, the sharp expansion around the obstacle causes the lower part of the detonation to fail, whereas the upper part continues as a normal multiheaded wave. Reflection from the top wall further enhances the detonation, and, in the last two frames, the self-sustained cellular detonation near the top wall eventually will sweep

down to reinitiate the decoupled complex of the diffracted wave. The obstacle now acts to play a positive role in assisting the reinitiation process, while simultaneously playing a destructive role causing failure by diffraction.
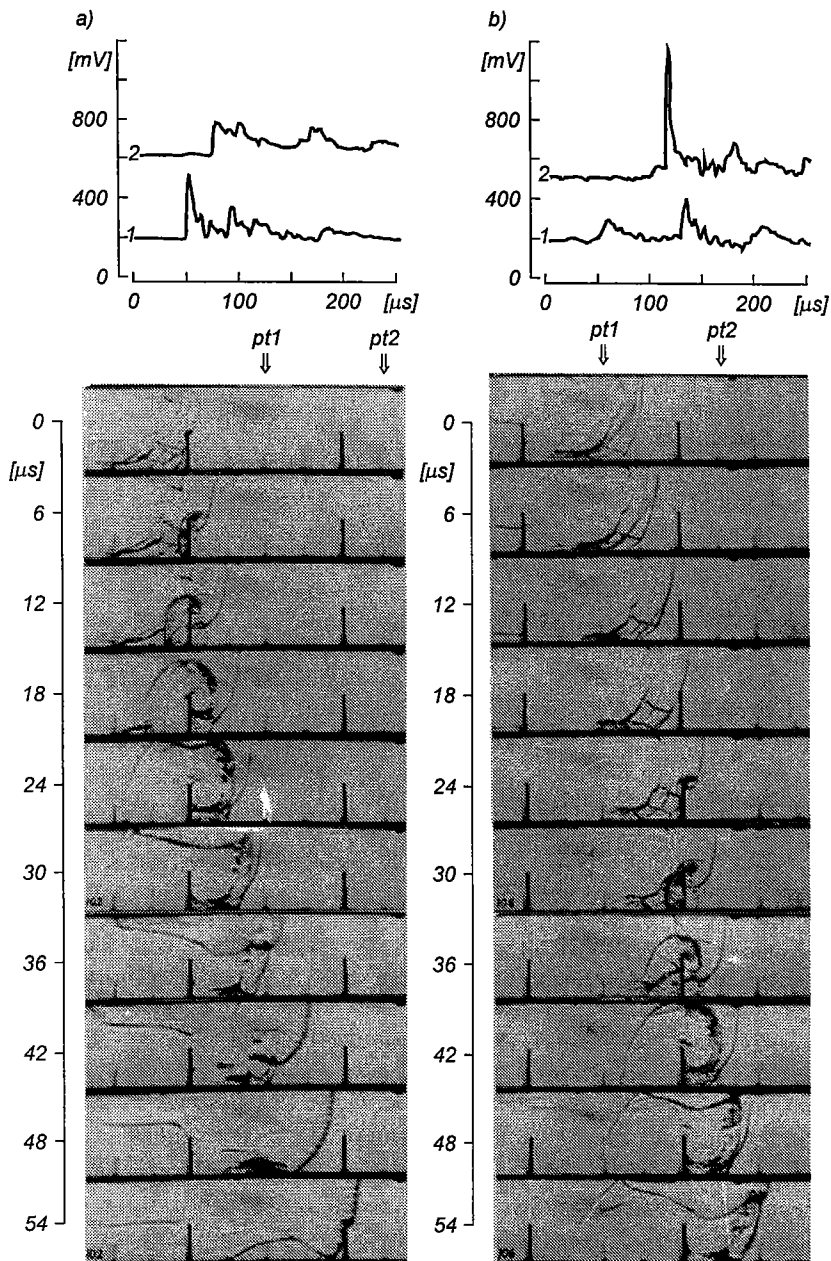

Fig. 15. Propagation of quasi-detonation in obstacle array in $2H_2 + O_2$ mixture: a) and b) initial pressure — 120 torr

Figure 15a shows a similar reinitiation process due to reflection of the Mach stem from the obstacle. The rapid expansion of the reflected shock due to autoexplosion is clearly evident by comparing frames 2 and 3. In the present case, the diffraction causes the reinitiated detonation to fail, and it becomes a cylindrical deflagration with progressive decoupling of the reaction zone from the shock front. However, the normal reflection of the leading shock from the top wall causes a reinitiation process. The cellular detonation subsequently sweeps down to engulf the entire decoupled front. The accompanying pressure records are also shown, and the location of the pressure transducers in the channel are indicated by PT1 and PT2. The first transducer records the large pressure rise at the moment of autoexplosion at the top wall caused by normal reflection of the cylindrical shock wave. The second transducer registers the cellular detonation pressure prior to its destruction by diffraction.

A similar reinitiation by Mach stem reflection from the obstacle is clearly demonstrated by the case shown in Fig. 15b. Of interest are accompanying pressure traces from the two transducers. The first transducer records a series of weak shock waves typical of a fast deflagration driven by a turbulent reaction zone. The pressure trace from PT2 records the failing cylindrical deflagration with the shock slightly decoupled from the reaction front. However, when the shock reflects from the top wall, an extremely high pressure peak typical of a transition process is recorded. The subsequent overdriven detonation near the top wall is clearly evident in the last frame.

Depending on the obstacle height and spacing, as well as on the vertical height of the channel, one or more of the above-described mechanisms can occur. It is doubtful that a general description of the structure of a quasi-detonation can be obtained. However, it may be said that the propagation mechanism is one of continuous reinitiation and attenuation by diffraction around the obstacles. This mechanism essentially is identical to that of a normal detonation, where reinitiation occurs when transverse waves collide and the reinitiated wave fails between collisions. In quasi-detonations, the reinitiation is controlled by obstacles.

5. EFFECT OF OBSTACLE GEOMETRY

In view of the essential role of the vortex zones in the transition and propagation processes of quasi-detonations, the obstacle geometry was altered to suppress or accentuate the obstacle induced vortex flow structure. In the first instance, a ramp was installed upstream of each obstacle to alter the bottom wall reflection of the diffracted wave. This in effect delays the onset of the

Mach reflection on the bottom wall. Figure 16 illustrates the propagation of a quasi-detonation over such an obstacle field. The sequence of photographs shows that the onset of the Mach reflection has been delayed to almost the upper apex of the obstacle at which its effect appears to merge with the explosion in the vortex downstream of the obstacle edge. The front surges forward and the reflected wave sweeps upward as a detonation wave through the decoupled reaction zone of the upper portion of the front. To all intents and purposes this particular modification to the obstacle geometry does not appear to have any significant adverse effect on the ability of the quasi-detonation wave to propagate. This is confirmed in the velocity plot of Fig. 17 where the transition boundary is identical to that of straight baffle obstacles.

If now a ramp is installed on the downstream side of the obstacle, then the severity of the diffraction is reduced. However, by the same token the scale and intensity of the vortex field is also suppressed. This is evident in Fig. 18a in which a combustion wave propagates in stoichiometric hydrogen-oxygen mixture at 100 torr initial pressure. At this initial pressure and with plain baffle obstacles or with forward facing ramps one would manage to get quasi-detonation propagation. In this case, however, with the backward facing ramp it is quite apparent that the strength of the exploding vortex on the downstream side of the apex (frames 11 to 15) is much smaller and weaker. The exploding of the pocket formed by the mixing in the apex of the ramp is incapable of reinitiating a detonation. Figure 18b shows (also Fig. 17) that only at initial pressure 120 torr can the front of a flame manage to propagate as a quasi-detonation wave. In this case the wave is not severely decoupled and the weakly exploding pockets at the apex of the ramp and at the top wall of the channel manage to sustain the wave overall.

Installing ramps on both sides of the obstacle for the same spacing means that the downstream diffraction is marginally more severe than the previous case. Since the upstream ramp has been shown to have a virtually negligible positive influence on the ability to propagate, then here the overall capability is marginally weakened. In Fig. 19a the propagation of the wave is at initial pressure 110 torr and it is as a high speed turbulent flame. Figure 19b clearly indicates that at initial pressure 130 torr the combustion wave propagates as a quasi-detonation wave over a double-sided ramp obstacle array.

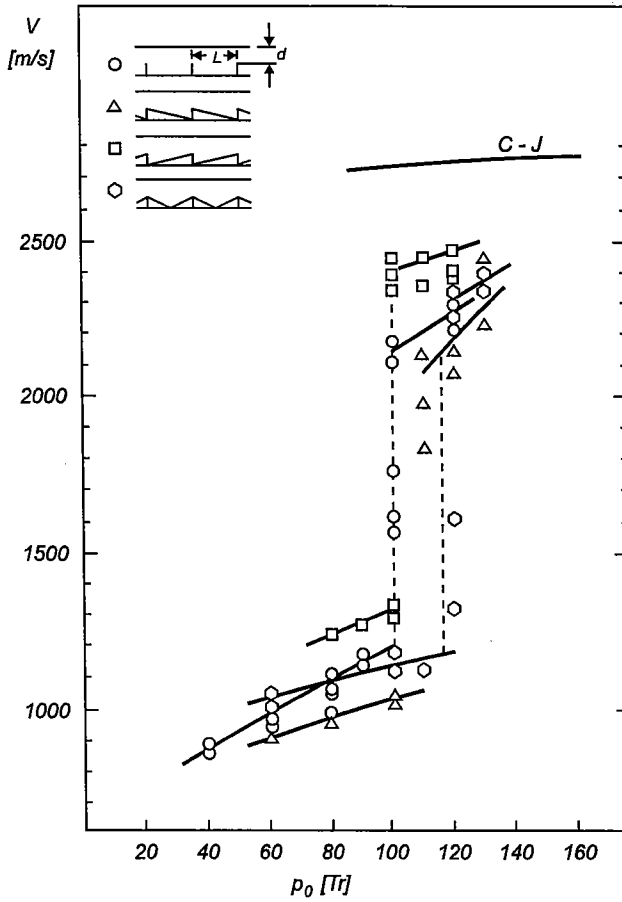Fig. 16. Propagation of quasi-detonation over forward facing ramp obstacles: $2H_2 + O_2$ mixture, initial pressure − 110 torr

Fig. 17. Variation of terminal steady-state velocity of the combustion wave with mixture reactivity (initial pressure) for ramp obstacles: $2H_2 + O_2$ mixture; $L/d = 2.5$
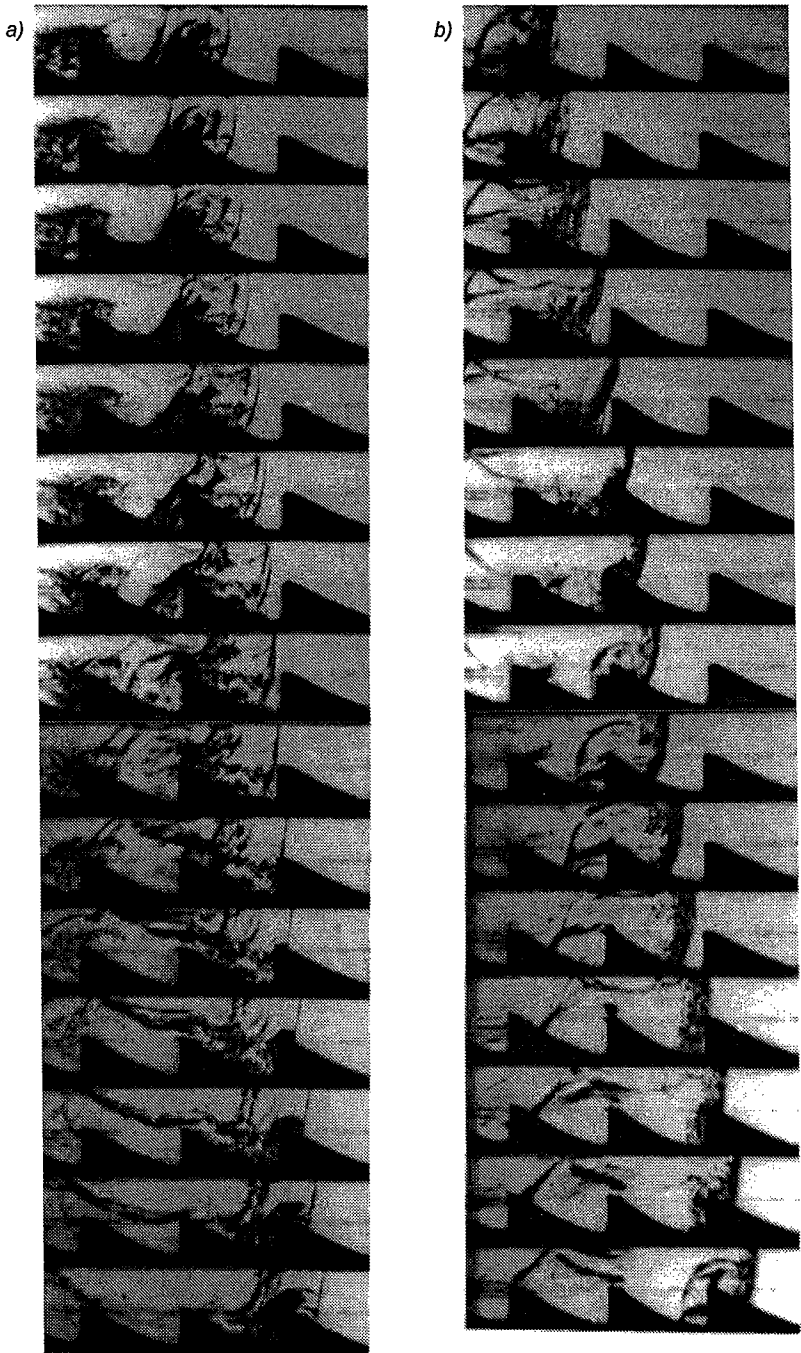
Fig. 18. Propagation of quasi-detonation over backward facing ramp obstacles in $2H_2 + O_2$ mixture: a) initial pressure — 100 torr; b) initial pressure — 120 torr
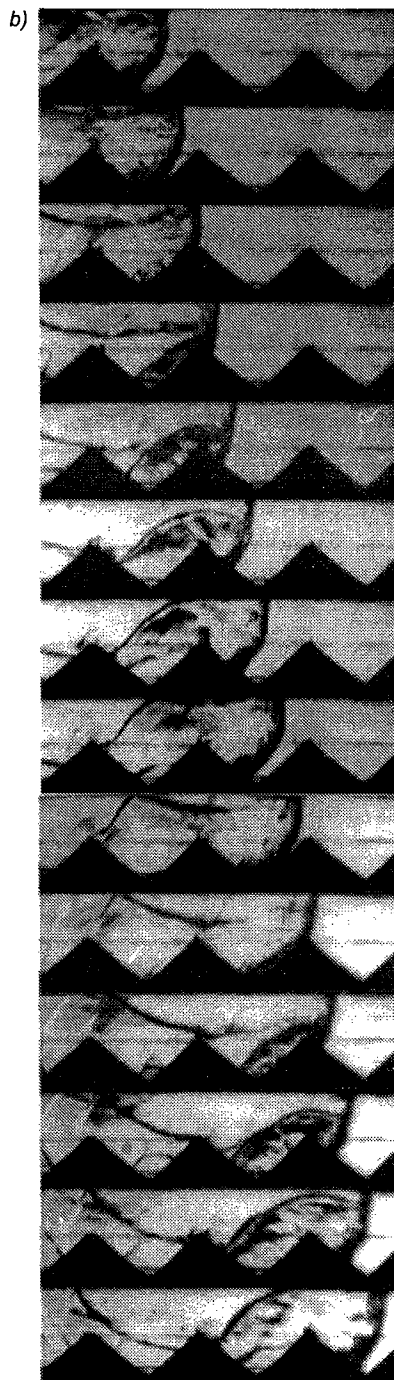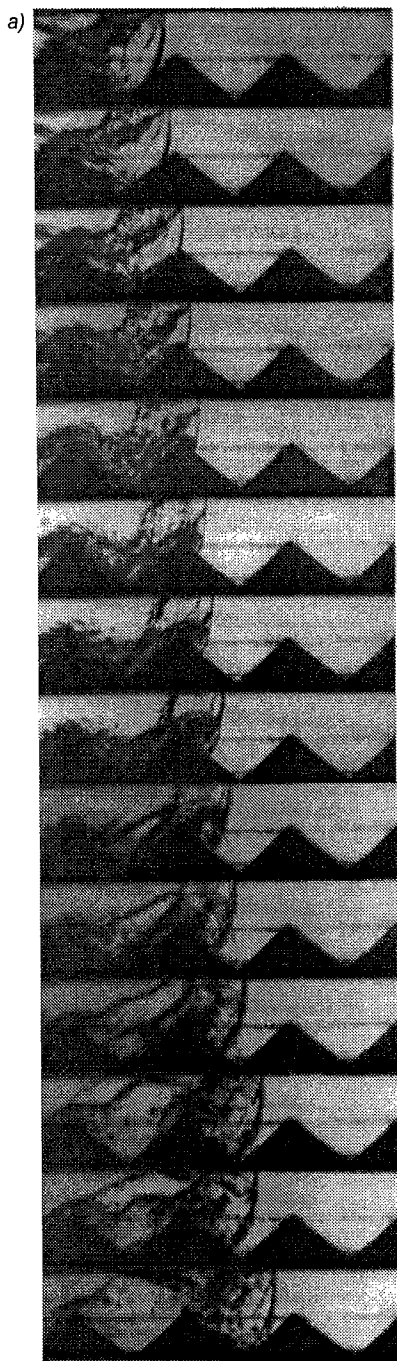
Fig. 19. Propagation of quasi-detonation over double-sided ramp obstacles in $2H_2 + O_2$ mixture:
a) initial pressure — 110 torr; b) initial pressure — 130 torr

CONCLUSIONS

The present study shows that in the fast deflagration regime of combustion in obstacle-filled channels shock reflections do not lead to autoignition. The mechanism for sustaining the fast propagation speed is intense combustion via flame turbulization by:

(i)   shock-flame interactions,

(ii)   Rayleigh-Taylor instability as the flame is convected in an accelerating flow,

(iii)   autoignition by rapid entrainment and mixing in the large recirculating eddies behind the obstacles.

The importance of transverse waves (and their interaction with the flame) is clearly demonstrated since their elimination results in a significant decrease in the deflagration speed. The elimination of the transverse waves also greatly delays the onset of transition from the deflagration to detonation regime.

In the quasi-detonation regime, as in normal detonation, continuous periodic reinitiation by shock reflections constitutes the principal mechanism of propagation. Diffraction by the obstacles results in failure of the detonation by causing the diffracted shock to decouple from the reaction zone. As in normal detonation, quasi-detonation is also a cyclic process with the characteristic length scale controlled by the obstacle configuration. Three main shock reflection processes are observed:

(i)   regular (or Mach) reflection of the diffracted shock from the bottom wall of the channel,

(ii)   normal reflection of the Mach stem from the front face of the obstacle,

(iii)   normal (or Mach) reflection of the transverse shock from the top wall of the channel.

Depending on the obstacle height, spacing, and distance to the top wall, one or more of these three reinitiation mechanisms can occur.

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SZYBKIE DEFLAGRACJE I DETONACJE
W KANAŁACH Z PRZESZKODAMI

Streszczenie

Powszechnie wiadomo, że płomienie rozprzestrzeniające się w kanałach wypełnionych przeszkodami mogą osiągać bardzo duże prędkości, bliskie prędkości dźwięku w spalinach.

Niniejsza praca przedstawia wyniki szczegółowych badań takich szybkich płomieni przy użyciu fotografii smugowej. Badania wykonano w dwóch kanałach o przekroju prostokątnym, o różnych polach przekroju, wypełnionych równomiernie rozstawionymi przeszkodami. Wykazano, że bardzo duża prędkość propagacji płomienia jest wynikiem intensywnej turbulizacji strefy reakcji chemicznej na skutek: oddziaływania fal uderzeniowych z płomieniem, niestateczności Rayleigha-Taylora oraz samozapłonów w wirach recyrkulacyjnych za przeszkodami.

W pracy przedstawiono także wyniki badań procesu przejścia do detonacji oraz struktury i mechanizmów propagacji quasi-detonacji. Wyniki badań w sposób jednoznaczny wykazują, że podstawowym mechanizmem w procesie propagacji quasi-detonacji jest samozapłon w obszarach za odbitymi falami uderzeniowymi. Oddziaływanie przeszkód jest tu dwojakie: pozytywna rola przy reinicjacji detonacji w wyniku odbić fal uderzeniowych oraz rola negatywna polegająca na tłumieniu i rozpraszaniu fali detonacyjnej przez odbieranie ciepła i pędu. W skali makro przeszkody obniżają średnią prędkość propagacji detonacji.

БЫСТРЫЕ ДЕФЛАГРАЦИИ И ДЕТОНАЦИИ В КАНАЛАХ С ПРЕПЯТСТВИЯМИ

Краткое содержание

Общеизвестно, что пламена распространяющиеся в каналах выполненных препятствиями могут достигать больших скоростей, близких скорости звука. В этой работе представлены результаты подробных исследований таких быстрых пламен, достигнутые благодаря использованию полосной фотографии. Испытания велись в двух каналах с прямоугольным сечением, с разными полями сечения, равномерно выполненными расставленными препятствиями. Доказано, что очень большая скорость распространения пламени является результатом турбулентности зоны химической реакции в результате взаимодействия ударных волн и пламени, неустойчивости и самовоспламенений в рециркуляционных вихрях с препятствиями.

В работе представлены также результаты исследований процесса перехода к детонации, а также структуры и механизмов распространения квази-детонации. Результаты исследований однозначно показали, что основным механизмом в процессе распространения квази-детонации является самовоспламенение в пространстве за отраженными ударными волнами. Воздействие препятствий двояко: положительно при реинициации детонации в результате отражений ударных волн и отрицательно из-за гашения и рассеивания детонационной волны в результате отнятия тепла и количества движения. В больших масштабах препятствия снижают среднюю скорость распространения детонации.