Shock Waves (1995) 4:225–236

Shock Waves

Detonation attenuation by foams and wire meshes lining the walls

A. Teodorczyk[1], **J.H.S. Lee**[2]

[1] Warsaw University of Technology, Warsaw, Poland
[2] McGill University, Montreal, Canada

Received April 19, 1994 / Accepted October 18, 1994

Abstract. In the present study systematic photographic investigations were performed of detonation interactions with foams and wire meshes lining the channel walls. An initial cellular detonation wave was propagating along a damping section (acoustic absorbing walls) which removed the transverse waves associated with its cellular structure. In some cases the wave had failed and a fast deflagration wave (a shock followed by a decoupled flame) was obtained and propagated at about half the C-J detonation speed. The events were studied photographically using a high speed framing camera and smoked foils.

Key words: Detonation attenuation, Foams, Time resolved schlieren

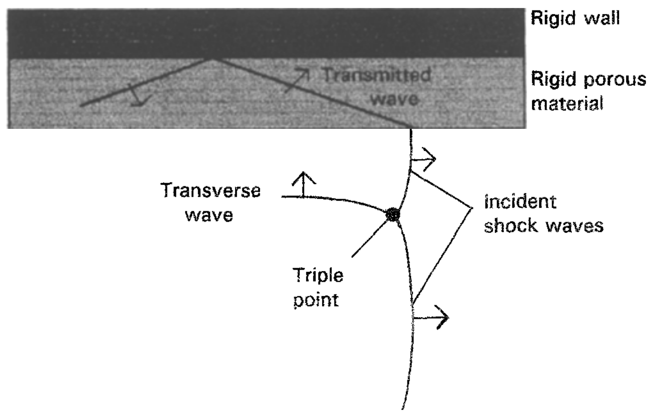

Fig. 1. The model of the detonation interaction with a porous wall

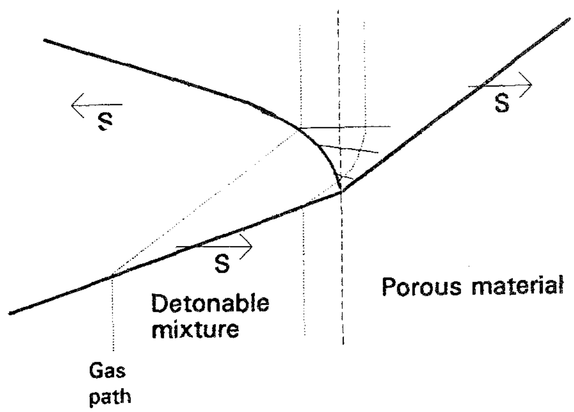

Fig. 2. Wave diagram of shock wave interaction with rigid porous material

1 Introduction

In chemical industries, explosive gas mixtures within the detonability limits may often occur in piping systems. Upon accidental ignition, the subsequent deflagration may transit to a detonation wave. For slow deflagrations, it may be possible to limit the pressure rise by venting. However, the detonation mode is too rapid for any venting system to be effective. Hence once a detonation is formed, quenching the detonation is the only effective means to stop its propagation into other parts of the system. Unlike slow flames a detonation wave is extremely difficult to quench. Existing detonation arresters always create a very high pressure loss in the line where they are installed. They are also unidirectional, i.e. they can arrest a detonation coming from one direction only. In many situations existing detonation arresters cannot be used.

The real structure of a detonation wave is very complex and comprises a number of interacting normal and transverse shock waves (Lee 1991). Shear layers are generated by the shock interactions which subsequently lead to turbulence. Chemical reactions occur in the highly non-uniform, transient, turbulent flow behind the multiple interacting shock complex. The ignition mechanism for a real detonation wave is not clear-cut. The high local temperatures generated by the shock interactions must play an important role. The intense turbulence behind these interacting shock waves also gives rise to rapid transport and mixing processes. These in turn can lead to ignition and a fast burning rate. Shocks and shock interactions always accompany intense compressible turbulence. Shocks provide extra dissipation mechanisms in addition to shear, and shock interactions in turn also generate

Correspondence to: Dr. A. Teodorczyk, Warsaw University of Technology, ITC Nowowiejska, 00-665 Warzawa, Poland

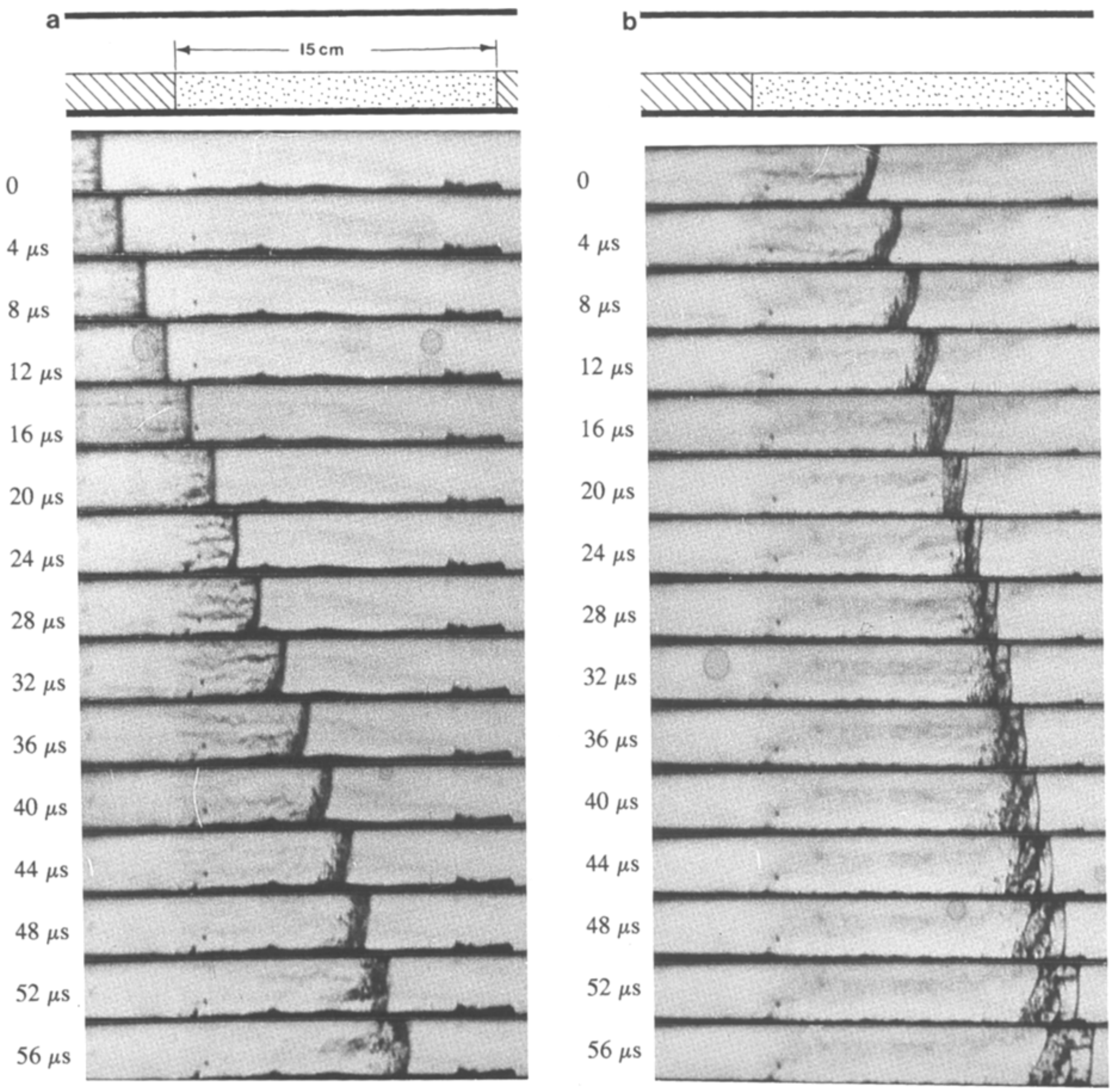

Fig. 3a,b. Damping of a detonation wave in $2H_2 + O_2$ mixture at $p_0 = 160$ hPa by the use of soft fiberglass wool for acoustic absorbing wall; two sequences of schlieren photographs, a and b

shear layers and "normal" turbulence. The important conclusion one derives from the above discussion is that shock interactions are essential to the propagation of a detonation wave. If the shock interactions are prevented by damping out the transverse waves, then the detonation will fail because the normal shock does not provide the required mechanism. Also it is apparent that, if one prevents transverse waves from developing, deflagration to detonation (DDT) can also be hindered.

The essential role of transverse waves in the stable propagation of a detonation wave is well known. When a detonation wave propagates in a rigid tube or channel, the rigid walls play a crucial role in the sustenance of the transverse wave structure. When a wall is removed such as in the case of the critical tube diameter, the transverse waves attenuate and may die out leading to a failure of the detonation wave. Even in porous or compliant-walled tubes there is attenuation of the transverse waves and hence of the detonation front. For example, in a porous walled material, Evans et al. (1955) found that the onset of detonation was delayed. In compliant thin plastic-walled tubes Murray (1985) observed that there is no progressive amplification of the transverse waves as a result of the reflection from the walls. Recently, Dupre et al. (1988) studied the propagation of detonation waves in tubes lined with metallic screen grids and showed conclusively that damping of transverse waves occurs and this affects adversely the ability of a detonation wave to propagate. Also recent numerical simulations by Reddy et al. (1988) have conclusively demonstrated the necessity for the presence of transverse waves for a detonation to propagate. A detonation wave fails when its transverse waves are attenuated by the acoustic absorbing wall of the tube. Teodorczyk et al. (1988, 1990) studied the role of transverse waves on the propagation of fast deflagrations and on transition and propagation of a quasi-detonation in very rough channels filled with obstacles. It was clearly demonstrated that the layers of fine

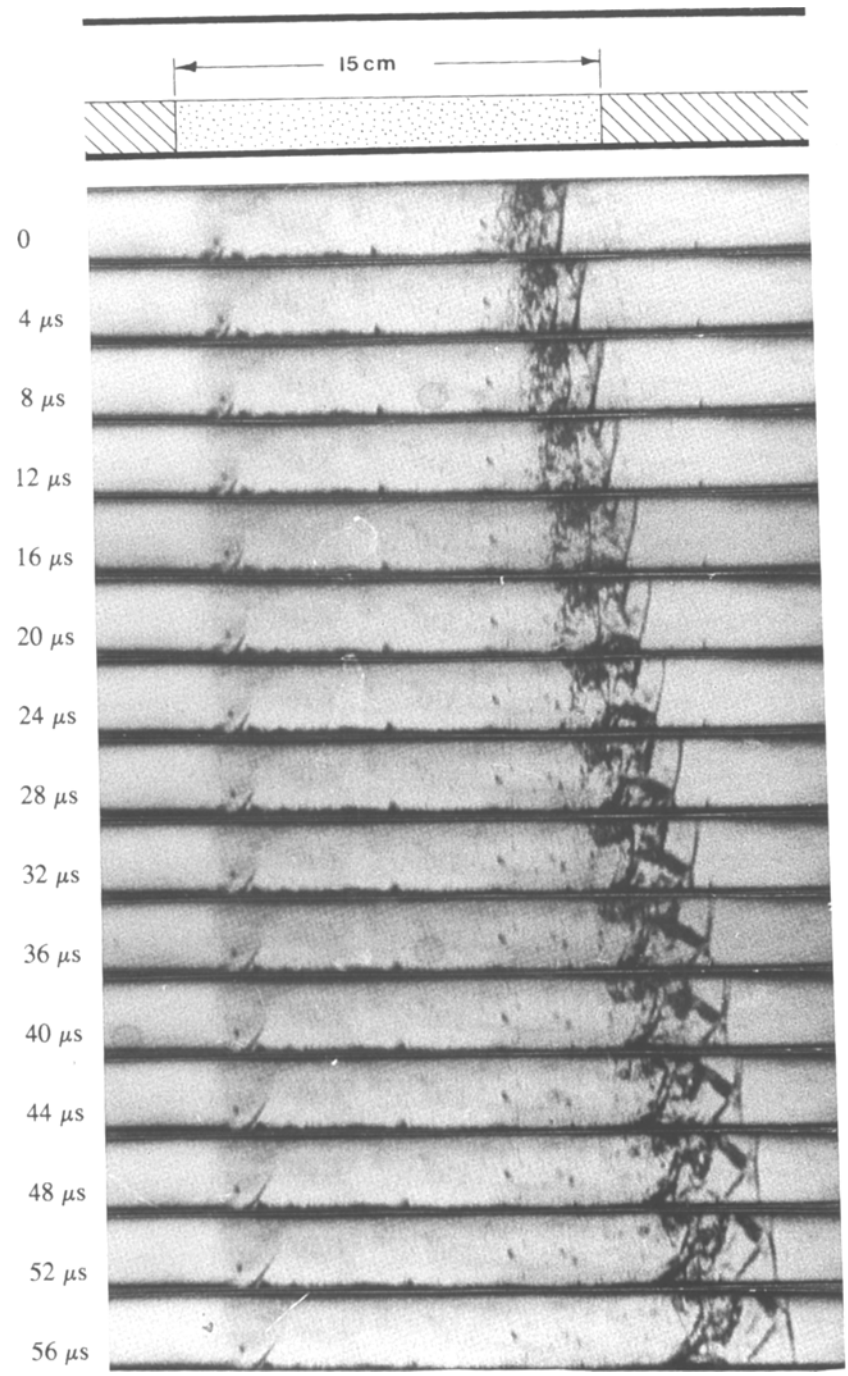

Fig. 4. Conditions similar to Fig. 3 but at later times

wire screens which were placed both on the bottom and top wall of the channel caused great delay of the transition to detonation. It was found that the placement of wire screens decreased the propagation velocity of fast deflagrations by about 200-300 m/s in the same geometry and mixture sensitivity.

Shock reflections from deformable porous materials (polyurethane or polyethylene foams) have been studied by numerous investigators over the past two decades (Gvozdeva et al. 1986, Levy et al. 1993, Mazor et al. 1994, Gelfand et al. 1983 and Monti 1970). From the point of view of using foam for detonation attenuation, perhaps the most significant finding from these previous studies is that, at an early stage

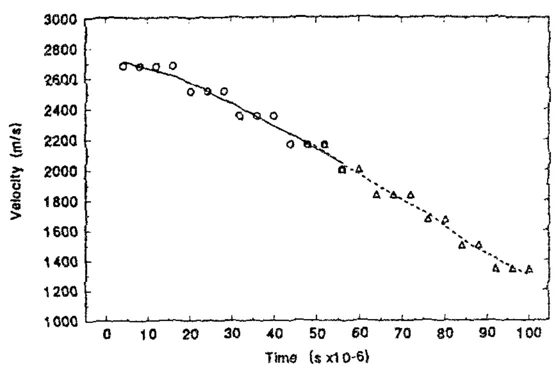

Fig. 5. Velocity versus time diagram for the detonation attenuation shown in Fig. 3: o experiment a; Δ experiment b

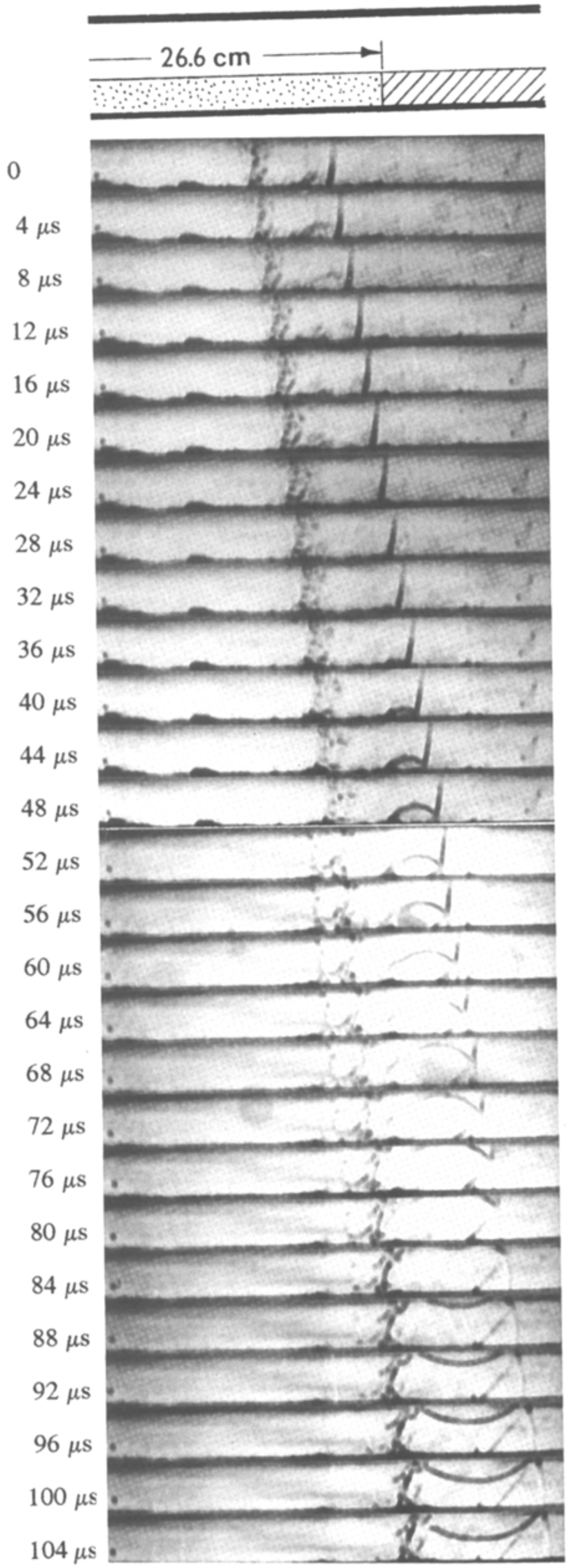

Fig. 6. Damping of a detonation wave by a 26.6 cm long section of fiber-glass wool; $2H_2 + O_2$ at p_0 = 160 hPa

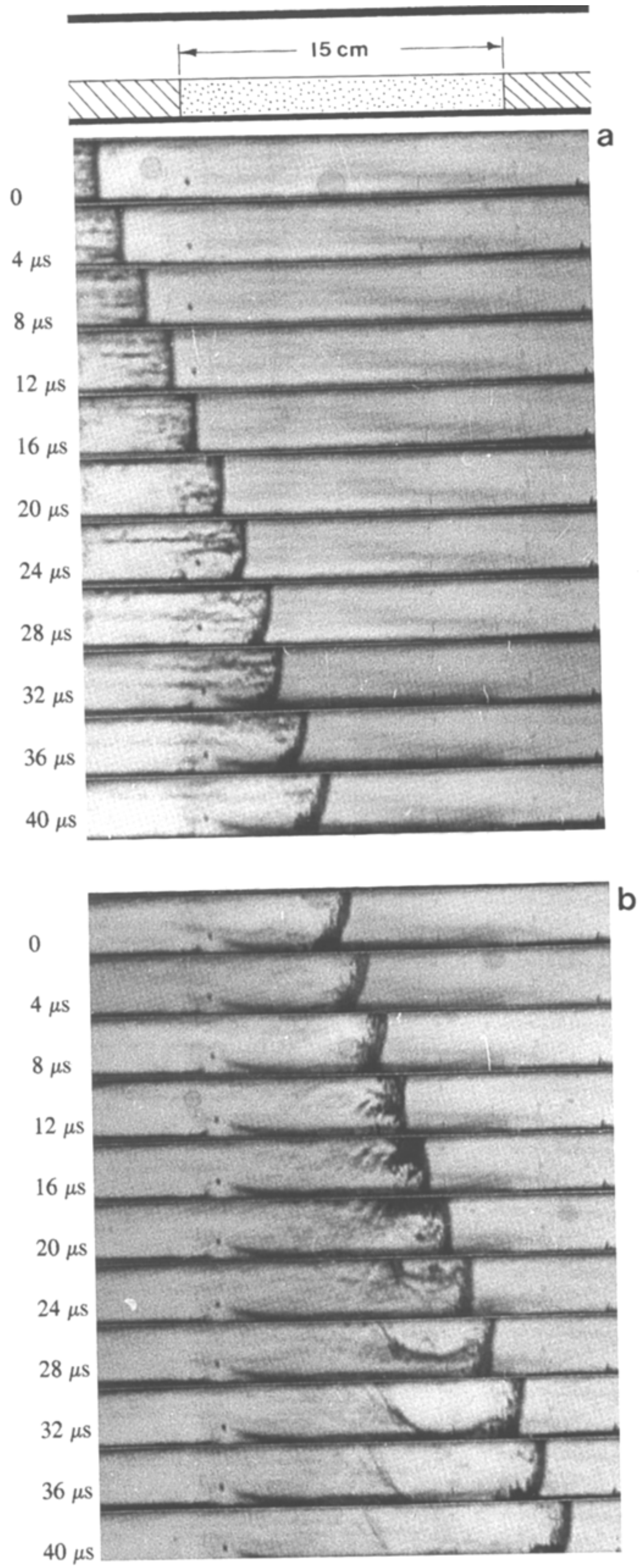

Fig. 7. Damping of a detonation wave by a 15 cm long section of soft open cell polyurethane foam; $2H_2 + O_2$ at p_0 = 160 hPa; two sequences of schlieren records, a and b

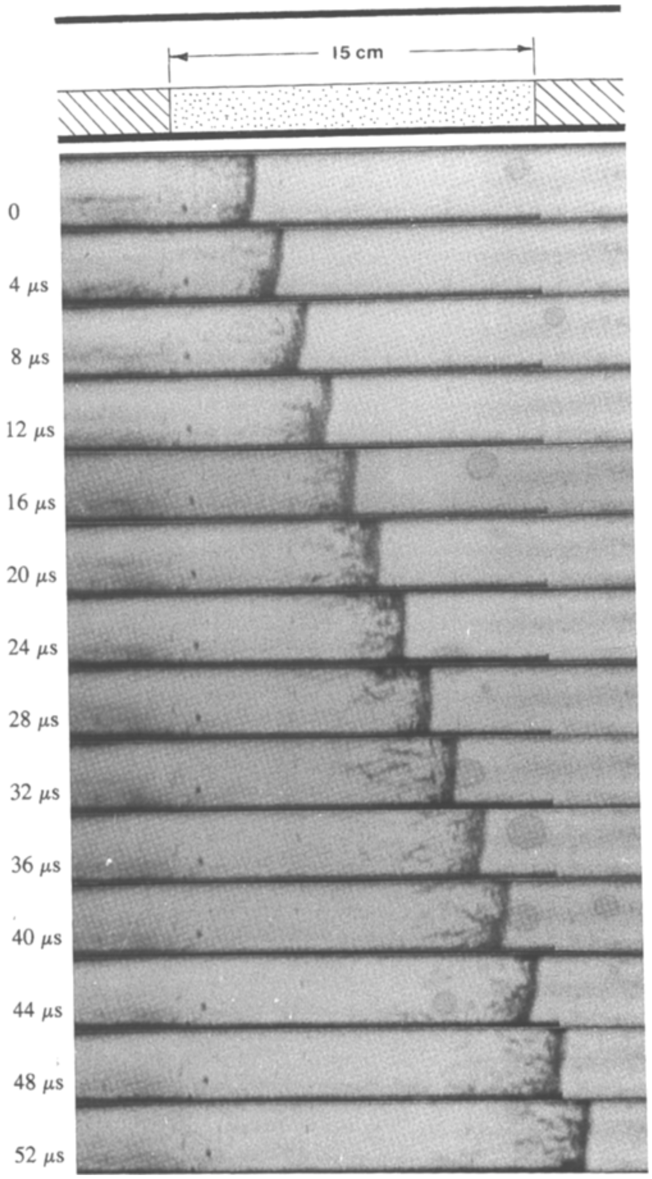

Fig. 8. Damping of a detonation wave by a 15 cm long section of a closed cell polyurethane foam; $2H_2 + O_2$ at $p_0 = 160$ hPa

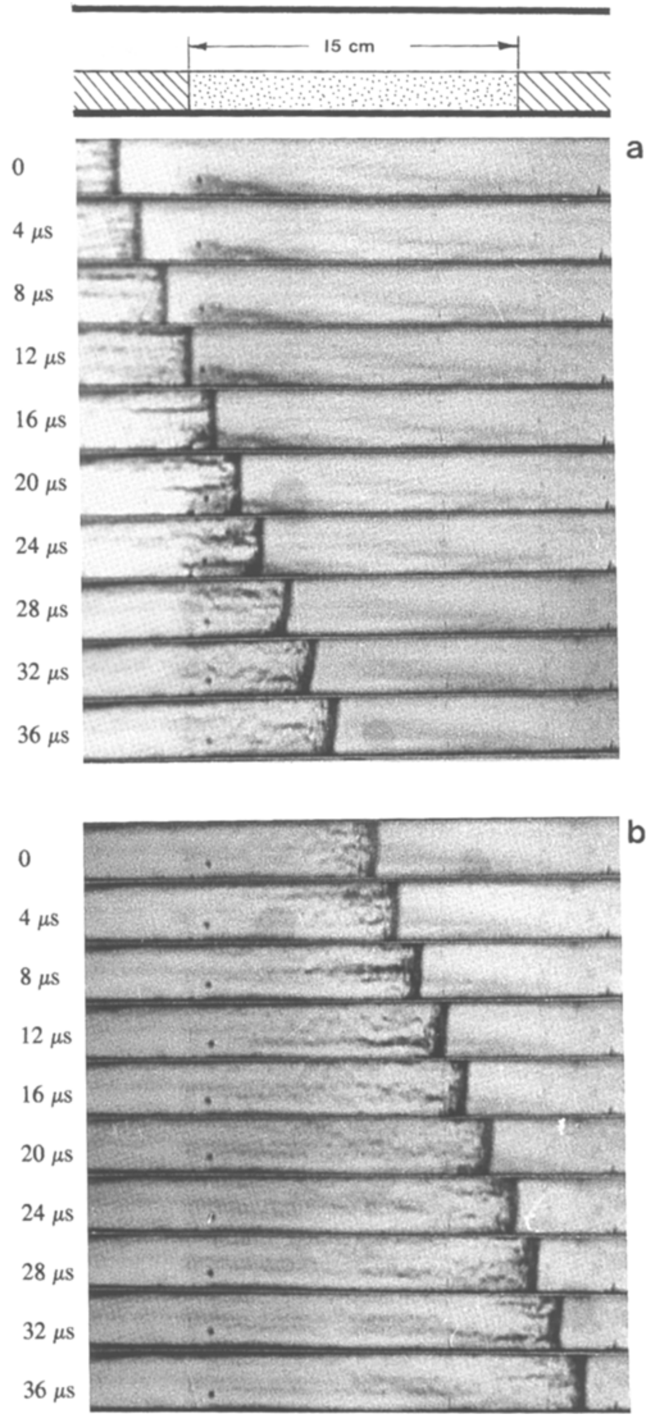

Fig. 9. Damping of a detonation wave by the use of a solid porous brick; $2H_2 + O_2$ at $p_0 = 160$ hPa; two sequences of schlieren photographs, a and b

of interaction, the pressure induced at the front edge of the porous material is smaller than the pressure induced by a shock wave reflecting head-on from a solid wall.

The objective of the present study was to perform a systematic photographic study of the propagation of detonation waves along a channel whose walls are covered by acoustic absorbing materials.

2 Interaction of a detonation wave with porous material

A simple model of the interaction of a multiheaded detonation wave with porous material lining the rigid wall is given in Fig. 1. Travelling from left to right the incident shock wave is transmitted into the body of the material when moving along the porous material lining the wall. The transmitted wave is reflected from the top rigid wall, propagates back through the porous material and is refracted at the gas/material interface. When the transverse shock wave strikes the porous wall, one shock is reflected from the surface of the material and another is transmitted into the body of the material.

Very little attention has been paid in the literature of the reflected wave field illustrated in Fig. 1. Some studies were reported on much simpler cases, i.e. attenuation of the shock wave travelling through a constant area duct uniformly perforated (Szumowski 1971, Wu and Ostrowski 1971) and normal shock reflection on a porous wall.

Levy et al. (1993) indicated that, following the head-on reflection of the incident shock wave from the front edge of the porous material, the pressure at the front edge does not rise sharply but keeps on increasing continuously. This effect could be explained by multiple reflections from the internal walls of the pores. The strength of the reflected wave is determined by the velocity of the gas behind it, which is determined both by the movement of the gas/porous material interface and whether any gas penetrates into the material. The porous material skeleton requires some finite time to accelerate and this causes continuous build-up of the strength of the reflected wave.

The same phenomenon was observed by Skews (1991) in his experiments with a compressible porous foam. The results also showed that the strength of the reflected wave was greatly reduced in comparison with rigid wall reflection. The observed rounded shape of the pressure trace may be explained using the wave diagram shown in Fig. 2.

When the waves strikes the porous face, wavelets will be reflected from the skeleton material giving an initial, weak reflected wave. The part of the shock striking the interstitial spaces will pass into the pores inducing a gas flow into the material. This gas will be decelerated due to friction and further reflections from the cell structures. The deceleration has the effect of causing compression waves to propagate back into the gas ahead of the porous material. The waves will catch up with the earlier reflection and coalesce with the reflected shock to form a stronger wave. For a flexible porous material there is an additional effect of interface motion.

The presented model largely simplifies the real case of a detonation passing along the porous material, and it deserves further detailed study.

3 Experimental

The experimental apparatus used in the present study consists of a 1.5 m long channel of rectangular cross section. The channel itself is constructed of steel beams as the upper and lower walls, with glass panes of optical quality forming the side walls. The glass is bonded to the side edges of the steel beams with silicon sealant which also assures that the resulting chamber is vacuum tight. The glass side walls provide a see-through capability of up to about 80 % of the channel length. The experiments were carried out mainly with a rectangular channel 57.2 mm wide and 32.5 mm or 48 mm high. Few experiments, the results of which are presented in Figs. 13 and 14 were performed in a channel 12.8 mm wide and 75 mm high. In a first series of experiments part of the lower wall was replaced by a segment of a compliant material. The materials used have been soft rock wool fiberglass (ρ = 37 kg/m^3, commonly in use for heat insulation), soft polyurethane open cell foam (ρ = 30 kg/m^3), closed cell polyurethane foam (ρ = 20 kg/m^3) and porous rigid brick (30 % porosity). For a second series of experiments layers of wire screens (0.25 mm wire diameter, 0.4 mm aperture, 43 % screening area) were placed inside the channel. All the experiments were carried out in stoichiometric oxy-hydrogen mixtures at an initial pressure of 160 hPa. At one end of the channel direct initiation of detonation in the mixture was achieved by a high voltage electric spark or exploding wire using a 100 μF capacitor charged to 4 kV.

Observation of the combustion waves was accomplished 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 dia 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 (KODAK TRI-X), typically 75 cm long. This provided up to 30 frames of single event photography up to a maximum framing rate corresponding to about 2 million frames per second. The camera was illuminated by a linear xenon flash lamp (Xenon Corp. FPA8100C) powered by a part of a solid state laser condenser bank (Maser Optics). The duration of the illuminating flash was about 1 ms at half peak intensity level. Synchronization of the events (ignition spark and illumination flash) was achieved via two BNC Corp. Model 7010 digital delay generators. The initiation of events originated from a pulse of a photodiode associated with the rotating mirror in the high speed camera.

4 Results

Figure 3 shows the propagation of a fully established C-J detonation wave (two separate experiments) over a strip of soft fiberglass wool placed at the bottom wall of the channel. The strip of fiberglass was 24.4 mm thick and 15 cm long. In the early frames on the left sequence (Fig. 3a) 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 notice that starting

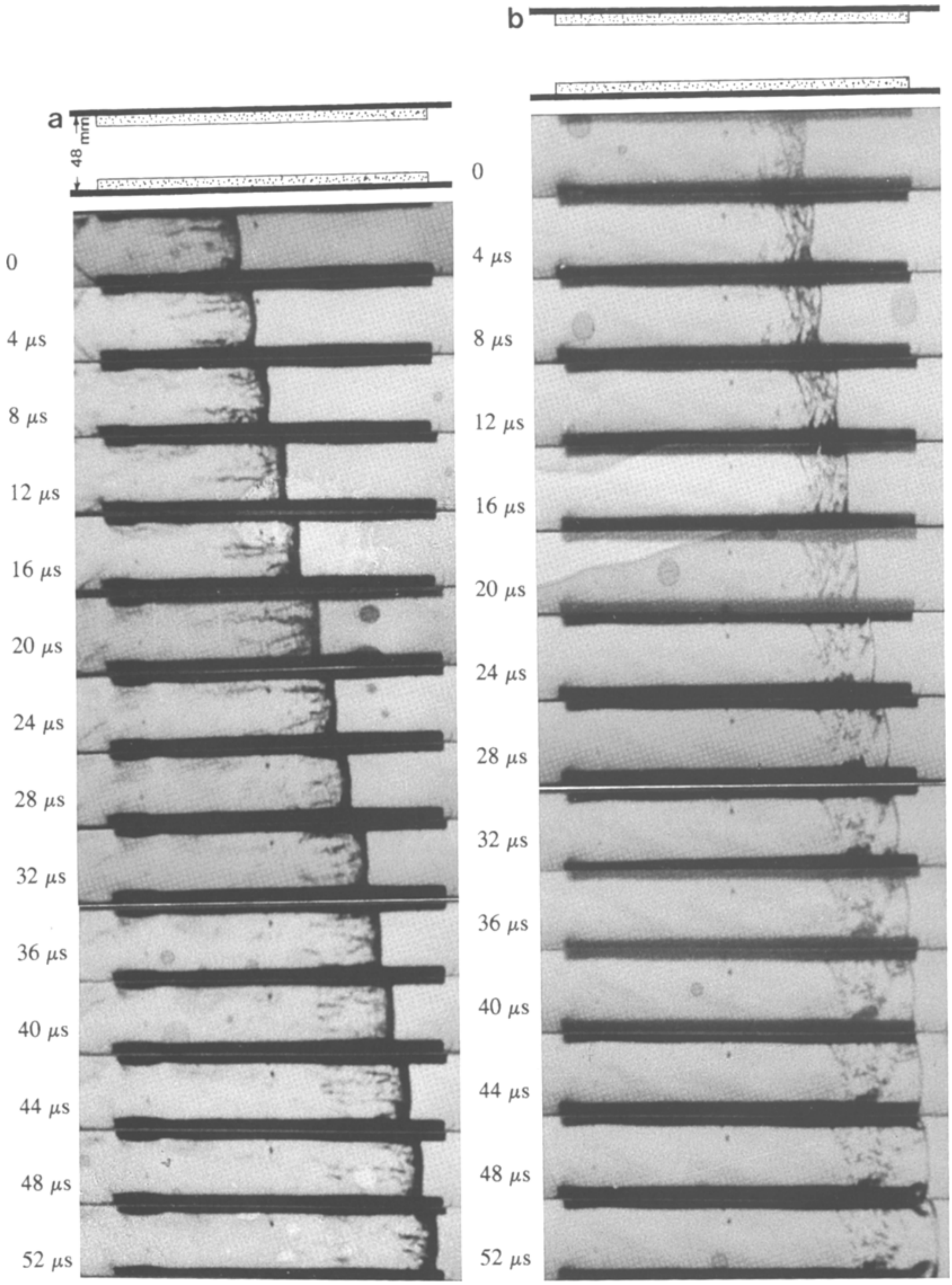

Fig. 10a,b. Detonation attenuation by a 20 cm long section of wire meshes lining the bottom and top wall of the channel; a) $2H_2 + O_2$ at $p_0 = 200$ hPa, detonation cell size $\lambda = 8.6$ mm ; b) $2H_2 + O_2$ at $p_0 = 133$ hPa, $\lambda = 14$ mm

at the 20 μs frame the horizontal striations begin to disappear progressively at the bottom of the wall so that by the 44 μs frame they are completely absent and the decoupling of the shock and reaction zone is seen to begin. On the right sequence of Fig. 3b the combustion wave becomes completely and progressively more decoupled in the later stages of propagation over the compliant wall segment. Figure 4 shows the attenuated wave re-emerging onto the rigid wall. Although this induces a transverse reflected shock and Mach configuration, the rigid wall is unable to restore the detonation wave at least not within the field of view of the present sequence of photographs.

The combustion wave speed during its propagation along the damping section has been calculated from Fig. 3 and is given in Fig. 5. It is clear that the velocity decreases continuously during the detonation attenuation reaching about half

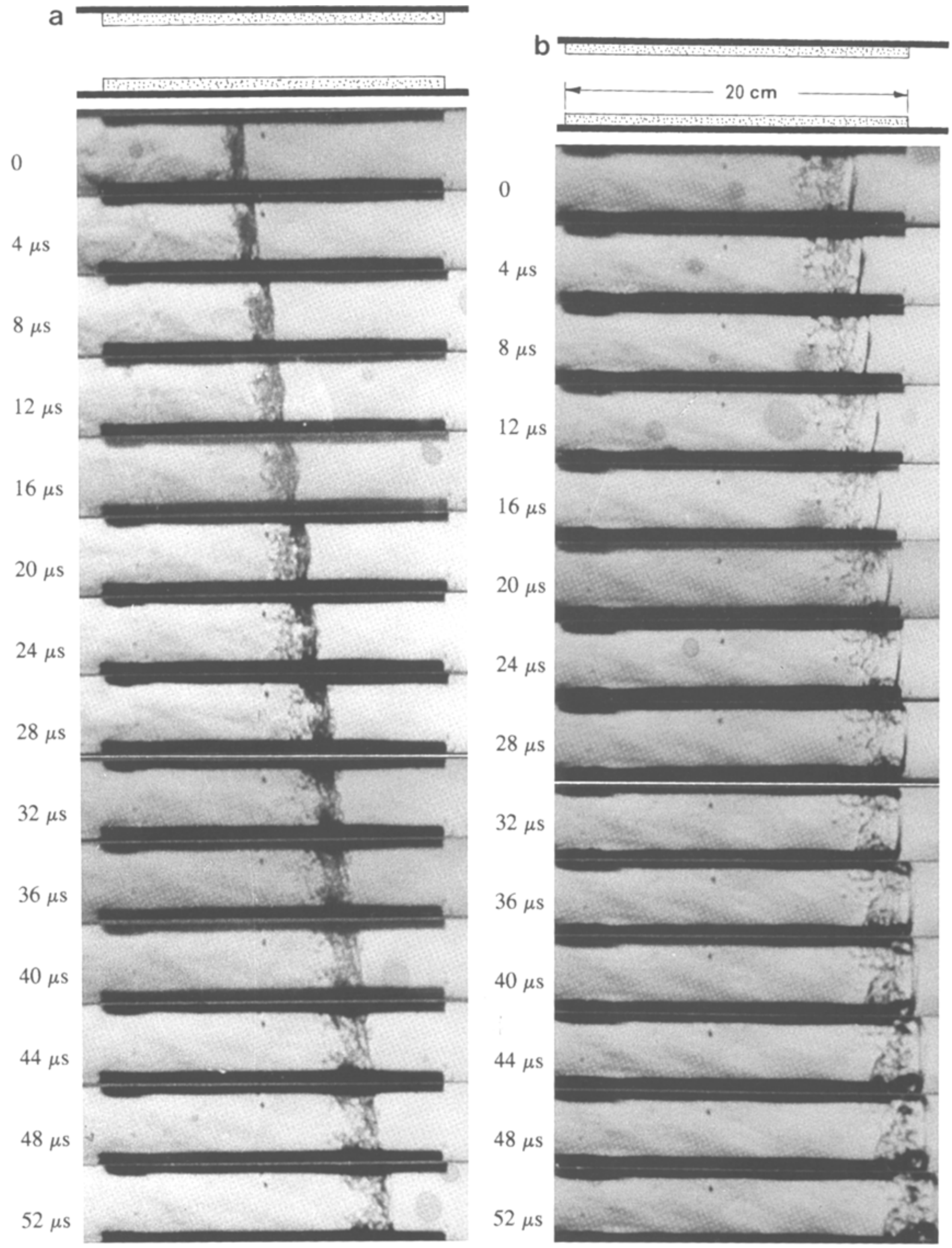

Fig. 11a,b. As in Fig. 10: $C_3H_8 + 5O_2$ at $p_0 = 40$ hPa; two sequences of schlieren records; $\lambda = 36$ mm

the normal C-J detonation velocity value when the shock wave and the reaction zone are fully decoupled.

Figure 6 shows the damping phenomenon for the same mixture but along a longer strip of fiberglass wool (i.e. 26.6 cm). Complete decoupling of the shock from the reaction zone is clearly evident. Again a transverse wave is generated when the shock hits the corner when it re-enters the solid wall section. Once decoupled, the reaction front can be damped easily by conventional flame arresters if desired. These figures give conclusive evidence of the quenching of a fully established detonation wave by lining the walls of the detonation tube with acoustically absorbing material.

Figure 7 shows the propagation of a C-J detonation wave over a soft open cell polyurethane foam. In this case the damping wall segment is not as compliant as with fiberglass but one still notices a progressive, albeit slower disappearance of the transverse striations. The separation of the shock from the reaction zone is not observed in this case. The wave

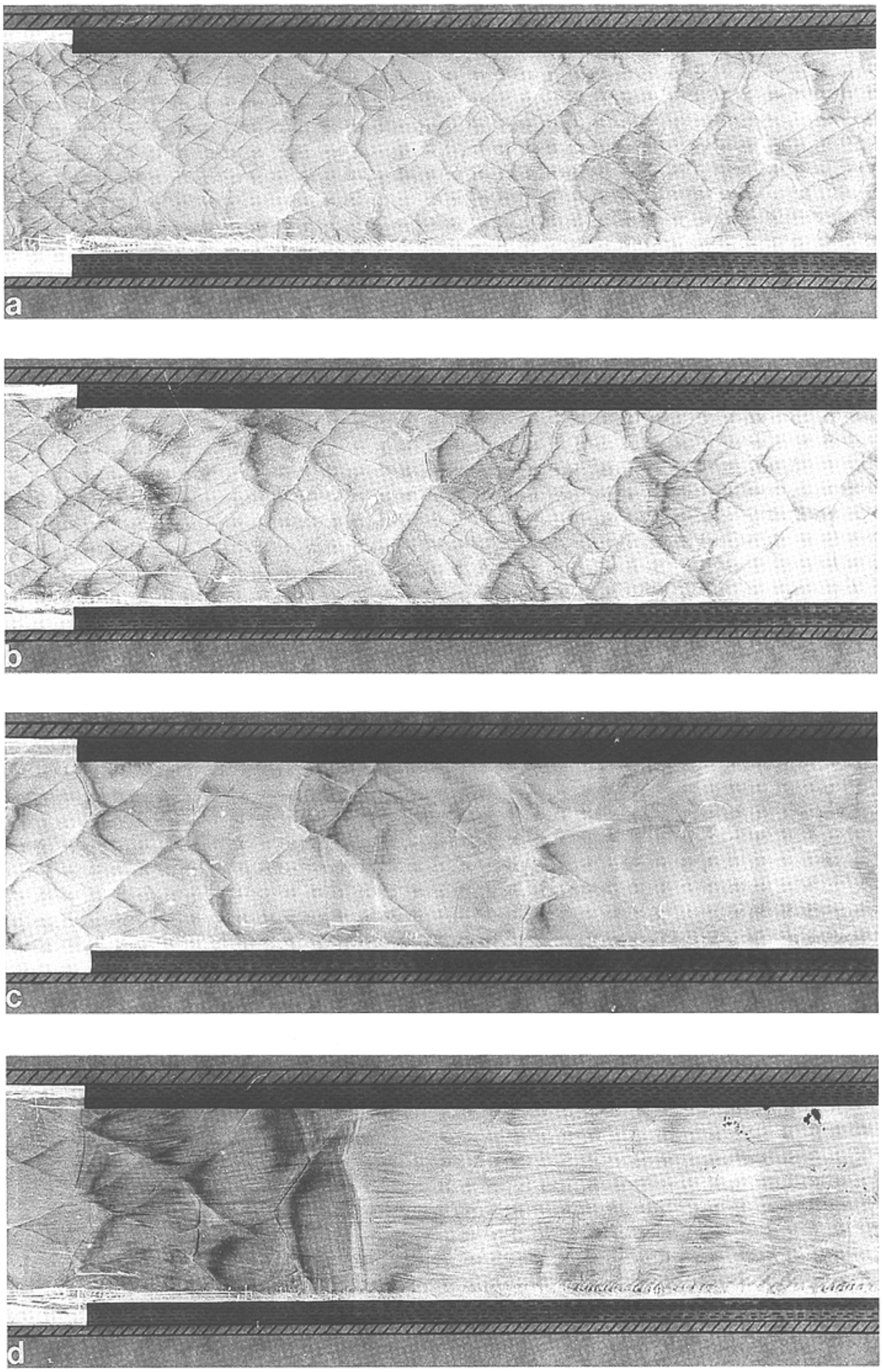

Fig. 12a–d. Smoked foil records of detonation attenuation by a 20 cm long section of wire meshes lining the bottom and top wall of the channel; $2H_2 + O_2$ at: a) p_0 = 187 hPa, b) p_0 = 160 hPa, c) p_0 = 107 hPa, d) p_0 = 93 hPa

front is observed to tilt and a Mach reflection appears to develop at the compliant wall (between 8 μs and 12 μs frames on sequence b). The resulting transverse wave moves upward and reflects from the top rigid wall. This seems to succeed in sustaining the front until it again manages to reach the rigid boundary and continues to propagate without failure. Clearly this is a marginal case.

Figure 7 indicates that after a maximum degree of attenuation the detonation wave appears in the later frames. The velocity of the wave in Fig. 7 appears to change little, unlike the cases in Figs. 3, 4 and 6 when the shock completely decouples from the reaction zone and the wave speed drops to about half its normal C-J detonation value.

Figure 8 shows the results with a closed cell polyurethane foam. In this case no gas flow into the foam is possible. Again, similar damping characteristics are observed but the slightly attenuated detonation wave is less tilted than in the previous case and there is no Mach reflection.

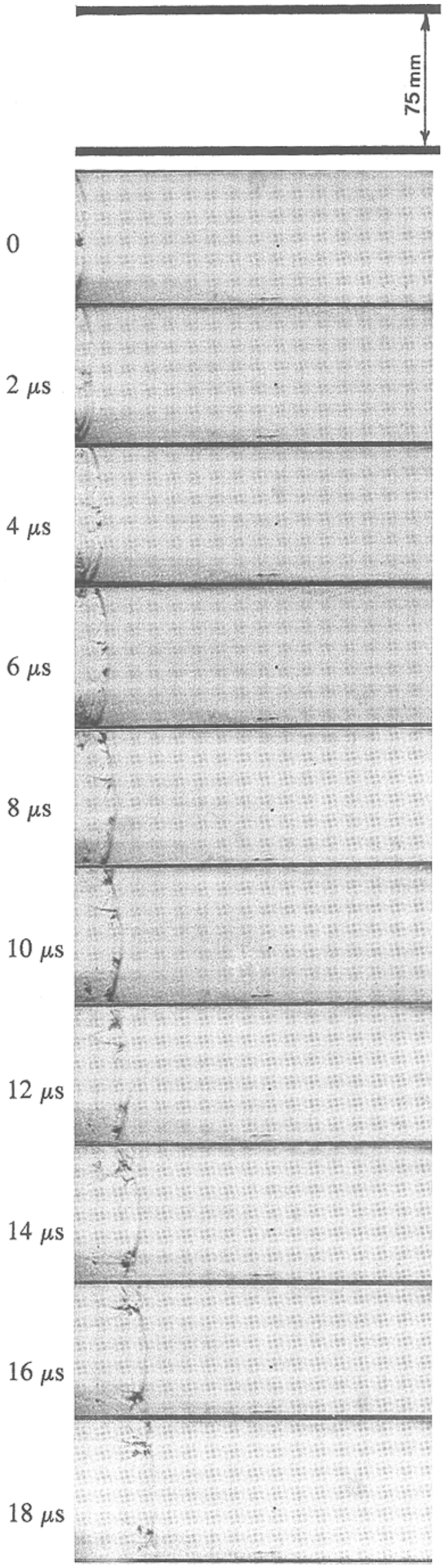

Fig. 13. Schlieren photographs of a detonation wave in $2H_2 + O_2$ mixture at p_0 = 67 hPa; rigid walls of the channel; detonation cell size λ = 34 mm

Figure 9 shows the results when a porous rigid brick is used for the damping. Unlike previous cases where the wall can be deformed by the pressure rise across the detonation, the porous brick is solid and attenuation is only due to porosity of the material. Again, slight detonation attenuation along the porous wall is observed, very similar to the case of a closed cell foam.

Further experiments were carried out by using a stack of stainless steel wire mesh to line the bottom and top wall of the channel. In this case damping effectiveness can be controlled by using different numbers of screen layers and different mesh sizes. Figure 10a shows a detonation wave in stoichiometric oxy-hydrogen mixture at 200 hPa initial pressure propagating along the damping section of screen layers. The detonation cell size for these conditions is 8.6 mm, so there are 4.4 cells across the channel. The detonation wave attenuates and the reaction zone thickens, but no separation of the shock wave from the reaction zone is observed. However, when the initial pressure was decreased to 133 hPa (lower mixture reactivity), the complete decoupling of the shock wave from the reaction zone is observed (Fig. 10b). The cell size for $2H_2 + 0_2$ mixture at 133 hPa is 14 mm thus there are now 2.7 cells across the channel. Similar results obtained for a less reactive stoichiometric propane-oxygen mixture at 40 hPa initial pressure are shown in Fig. 11.

In the experiments with wire meshes lining the walls smoked foil technique was also used for visual observations of the detonation damping. Figure 12 shows the smoked foil records for detonations propagating in stoichiometric hydrogen-oxygen mixtures at 187 hPa, 160 hPa, 107 hPa and 93 hPa initial pressures in the channel with layers of wire meshes lining the top and bottom wall. For 187 hPa initial pressure only a slight growth of the detonation cell is visible with some irregularity in shape and size. For 107 hPa initial pressure and less, damping of the detonation wave can be observed indicated by the disappearance of the cell structure.

Figures 13 and 14 show sequences of schlieren photographs of detonations of stoichiometric oxy-hydrogen mixtures propagating in a narrow 12.8 mm channel.The photographs clearly show the structure of a detonation wave with leading shocks, triple points and transverse shock waves. Figure 13 shows the case of rigid walls. In Fig. 14 a layer of screen meshes 6 mm thick is placed on the bottom wall. The photographs conclusively show that the transverse shocks are damped out by the compliant wall resulting in detonation failure.

5 Conclusions

This photographic study gives conclusive supporting evidence that the use of appropriate, acoustically absorbing materials to line the channel walls can effectively attenuate a fully established detonation wave.

As the detonation wave propagates along the porous material its transverse shock waves are attenuated what eliminates the fundamental gasdynamic phenomenon in the detonation mechanism. This leads to a continuous decrease of the wave velocity down to about half the normal C-J deto-

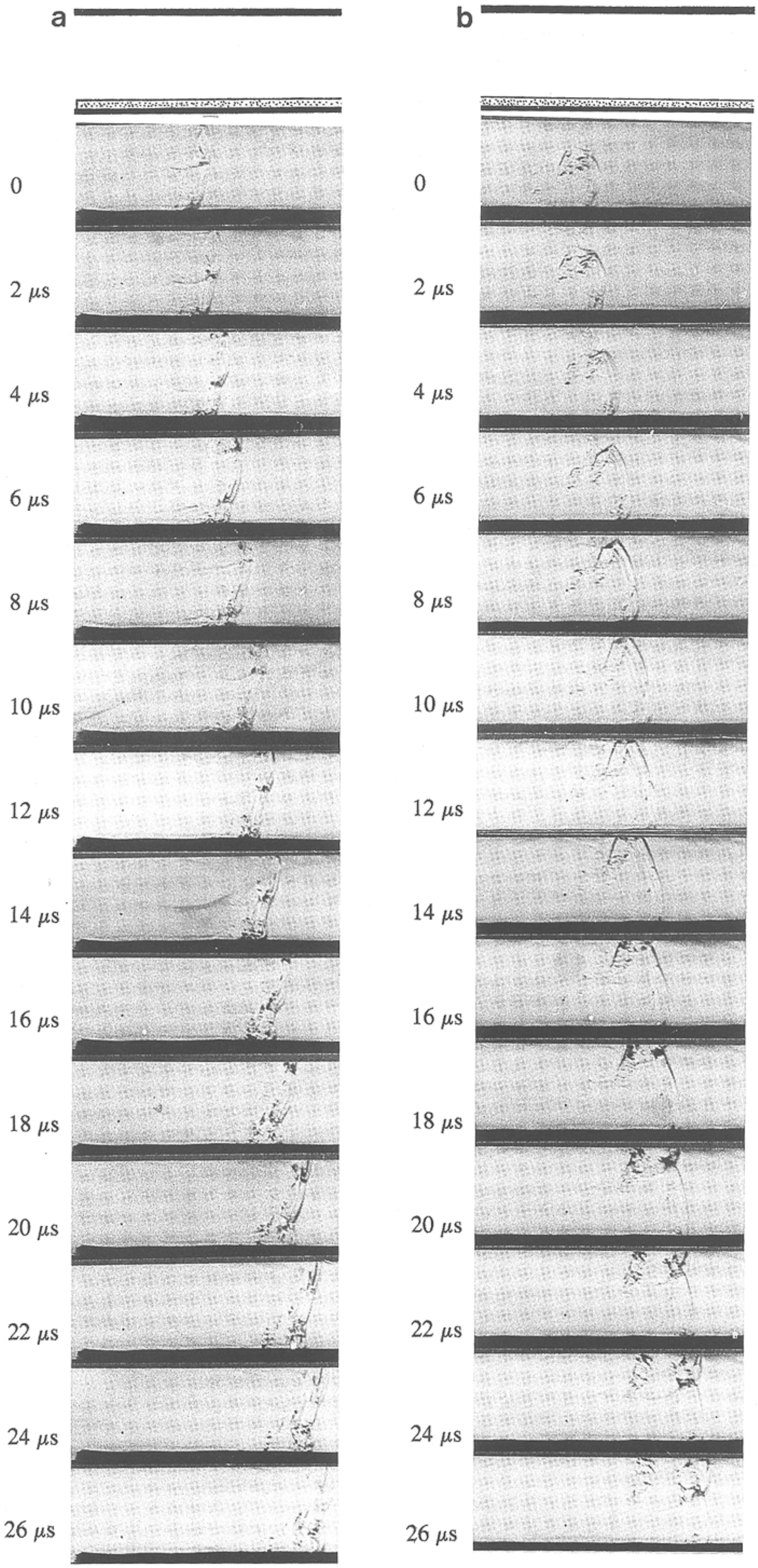

Fig. 14a,b. Two sequences of schlieren records of a detonation wave in $2H_2 + O_2$ mixture at 80 hPa passing over a 6 mm thick layer of screen meshes on the bottom wall; detonation cell size $\lambda = 27$ mm nation velocity when the shock wave and reaction zone are fully decoupled.

Open cell flexible materials (like fiberglass wool or polyurethane foam) are more effective in detonation attenuation than closed cell foams and rigid porous materials.

References

1. Dupre G, Peraldi O, Lee JHS, Knystautas R (1988) Propagation of detonation waves in an acoustic absorbing-walled tube. In: Kuhl AL, Bowen JR, Leyer J-C, Borisov A (eds) Dynamics of explosions. Prog. Astronautics and Aeronautics 114, AIAA Washington, 248-263
2. Evans MW, Given FI, Richeson WE (1955) Effects of attenuating materials on detonation induction distances in gases. J. Appl. Phys. 26: 1111-1113
3. Gelfand BE, Gubanov AV, Timofeev EI (1983) Interaction between shock waves and porous screen. Sov. Phys. Fluid Mech. 4: 79-84
4. Gvozdeva LG, Faresov YuM, Brossard J, Charpentier N (1986) Normal shock wave reflection on porous compressible materials. In: Bowen JR, Leyer J-C, Soloukhin RI (eds) Dynamics of explosions. Progress in Astronautics and Aeronautics 106, AIAA New York, 155-165
5. Lee JHS (1991) Dynamic structure of gaseous detonation. In: Borisov AA (ed) Dynamic structure of detonation in gaseous and dispersed media. Kluwer Academic Publishers, Dordrecht Boston London, 27-50
6. Levy A, Skews BW, Ben-Dor G, Sorel S (1993) Head-on collision of normal shock waves with rigid porous materials. Proc. 19th Int. Symp. on Shock Waves, Marseille (in press)
7. Mazor G, Ben-Dor G, Igra O, Sorek S (1994) Shock wave interaction with cellular materials. Shock Waves 3: 159-165
8. Monti R (1970) Normal shock wave reflection on deformable solid walls. Meccanica 4: 285-296
9. Murray SB (1985) The influence of initial and boundary conditions on gaseous detonations. Ph.D. Thesis, McGill University, Montreal, Canada
10. Reddy KV, Fujiwara T, Lee JHS (1988) Role of transverse waves in a detonation wave - a study based on propagation in a porous wall chamber. Memoirs of Faculty of Engineering of Nagoya University, Vol. 40, No. 1
11. Skews BW (1991) The reflected pressure field in the interaction of weak shock waves with a compressible foam. Shock Waves 1: 205-211
12. Szumowski AP (1971) Attenuation of a shock wave along a perforated tube. In: Stollery JL, Gaydon AG, Owen PR (eds) Shock tube research. Chapman and Hall, London, Paper 14
13. Teodorczyk A, Lee JHS, Knystautas R (1988) Propagation mechanism of quasi-detonations. 22nd Symp. (Int.) on Combustion, The Combustion Institute, 1723-1731
14. Teodorczyk A, Lee JHS, Knystautas R (1990) The structure of fast turbulent flames in very rough, obstacle filled channels. 23rd Symp. (Int.) on Combustion, The Combustion Institute, 735-741
15. Wu JHT, Ostrowski PP (1971) Shock attenuation in a perforated duct. In: Stollery JL, Gaydon AG, Owen PR (eds) Shock tube reesearch. Chapman and Hall, London, Paper 15