Journal of Hazardous Materials, 10 (1985) 125—139
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

A SCHLIEREN INVESTIGATION OF IGNITION DOWNSTREAM OF A FLAT-PLATE FLAME TRAP

G.A. LUNN and J. PRZYBYLSKI

Explosion and Flame Laboratory, Health and Safety Executive, Harpur Hill, Buxton, Derbyshire, SK17 9JN (Great Britain)

(Received September 11, 1984; accepted October 11, 1984)

Summary

High speed Schlieren photographs have been taken downstream of a flat-plate flame trap when the trap successfully arrests a flame and when it fails to do so. In all cases, burnt gases from the trap and fresh flammable mixture form a turbulent mixing region in which chemical reactions can occur. When the effects of these reactions can overcome the cooling effects of entrainment combustion takes place, and products form some distance behind the leading edge of the turbulent zone. However, combustion does not immediately lead to a self-propagating flame. Combustion reactions proceed in an essentially self-contained mixing region at the head of the turbulent plug for a delay time before an abrupt downstream pressure rise indicates that a self-propagating flame is formed.

Introduction

Flame traps are used in industry to extinguish accidental flames before they cause damage. Usually they consist of a series of narrow channels through which the flame cannot pass without being extinguished [1]. The re-ignition process downstream of a flame trap is not well understood. It is expected that re-ignition occurs in a mixing region of hot burnt gases and a fresh flammable fuel—air mixture somewhere in the downstream duct [2], but exactly where — whether close to the downstream edge of the trap or at a significant distance along the exhaust pipe — is not clear. A series of high-speed Schlieren photographs have been taken of the region downstream of a flat-plate flame trap in both ignition and non-ignition situations.

Experimental

A flat-plate flame trap has been made (Fig. 1) to fit in the explosion tube used with the Schlieren system (Fig. 2). The trap has a square cross-section of 41 × 41 mm. The length of the flame path through the plates is 50 mm, the gaps between the plates are 0.50 mm and the thickness of each plate is 1.25 mm. The upstream duct length is 1.23 m with spark

0304-3894/85/$03.30

ignition at the closed end; the downstream duct length is 1.6 metres from the downstream edge of the trap. The Schlieren apparatus used here transmits a beam of collimated light through a view field of 44.5 × 300 mm. The light source is a high-energy-spark generator that produces a series of eight sparks in air, each with a duration of 0.5 μs. The interval between sparks can be varied but the minimum interval is approximately 200 μs. The light is reflected through the field using concave mirrors and is focused onto the usual knife-edge. The Schlieren images are then captured by a drum camera. The experiments are done in darkness with the camera shutter open for the duration of the experiment and use of a fast film effectively isolates the images of the view field on the film.

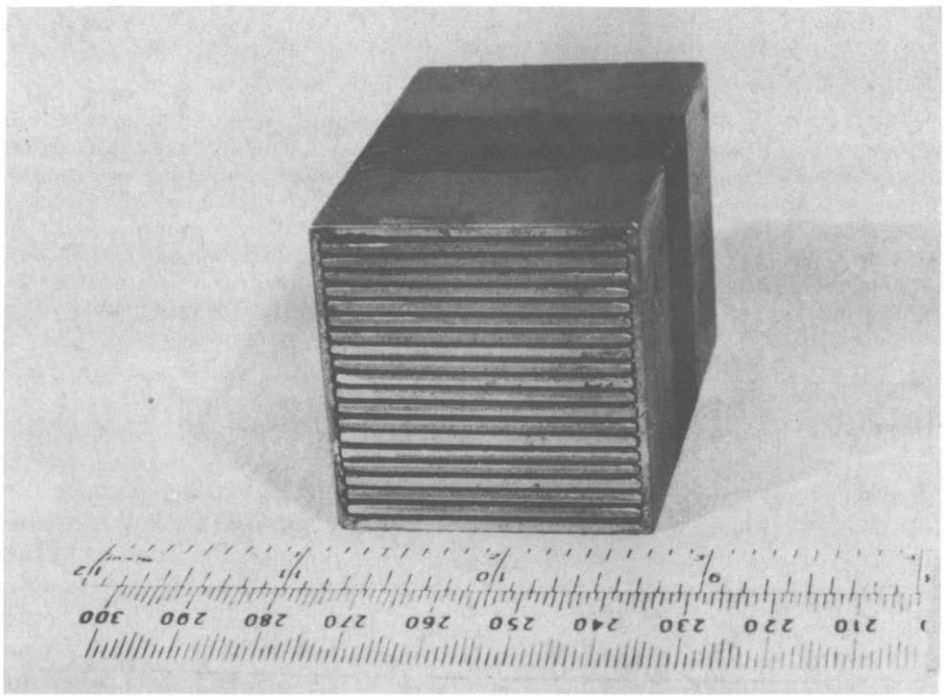

Fig. 1. The experimental flame trap.

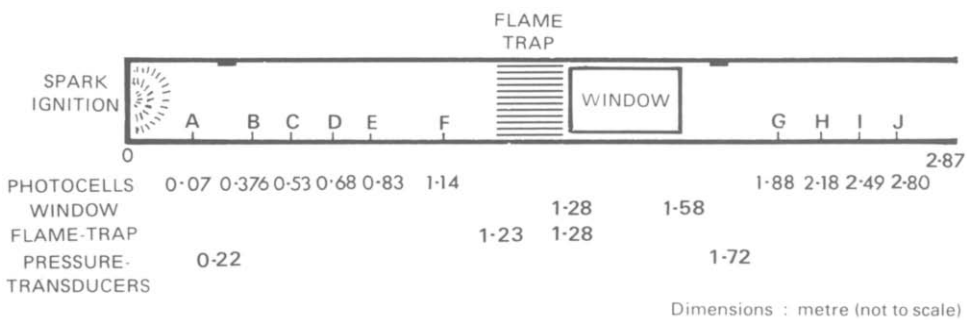

Fig. 2. The Schlieren tube.

The experimental procedure was to subject the trap to flames of methane —oxygen—nitrogen mixtures. Methane and oxygen were present in stoichiometric proportions and the nitrogen mole fraction varied from 0.70 to 0.52. Schlieren pictures were taken of the region downstream of the trap. The pressure—time profiles upstream and downstream of the trap were measured and photocell recordings of the flame movement taken.

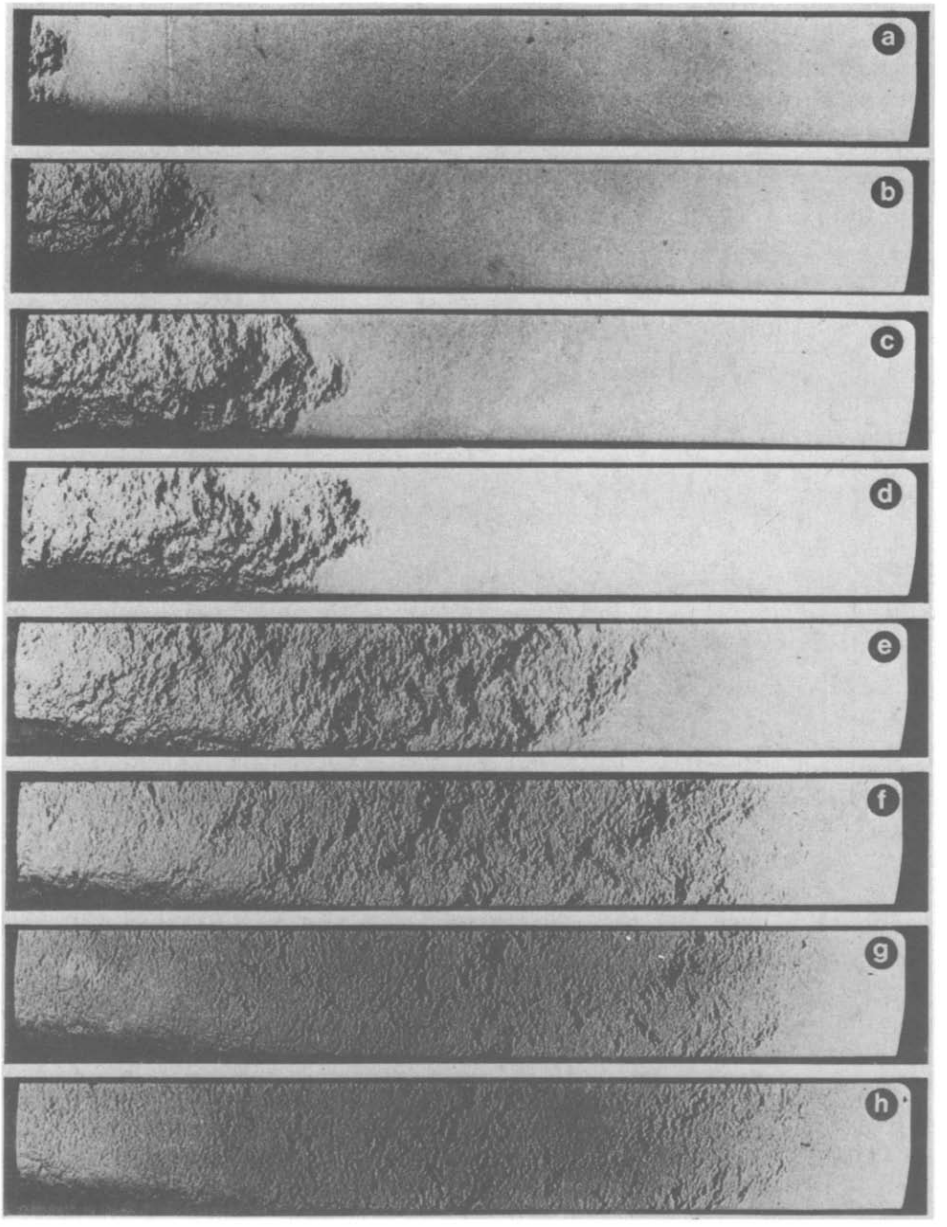

Fig. 3. Schlieren photographs for a nitrogen mole fraction of 0.65.

Results and discussion

As a flame moves towards a flame trap the unburnt gas between the advancing flame and the trap is compressed and undergoes a temperature increase before flowing through the flame trap. Figure 3 shows the Schlieren photographs for a methane—oxygen—nitrogen mixture with a nitrogen mole fraction of 0.65. The upstream pressure—time curve for Fig. 3 is shown in Fig. 4, along with the upstream photocell detection of the flame-front movement and timing of the Schlieren photographs. The taking of the Schlieren photographs was triggered by photocell F (Fig. 2). In this instance there was no downstream re-ignition. No discernible pressure rise occurred downstream of the flame trap.

Hot burnt gases that are ejected from the downstream edge of the trap are clearly distinguishable from the surrounding gas (Fig. 3, frame (a)). The hot gas is not always uniformly ejected from the trap; ejection can be

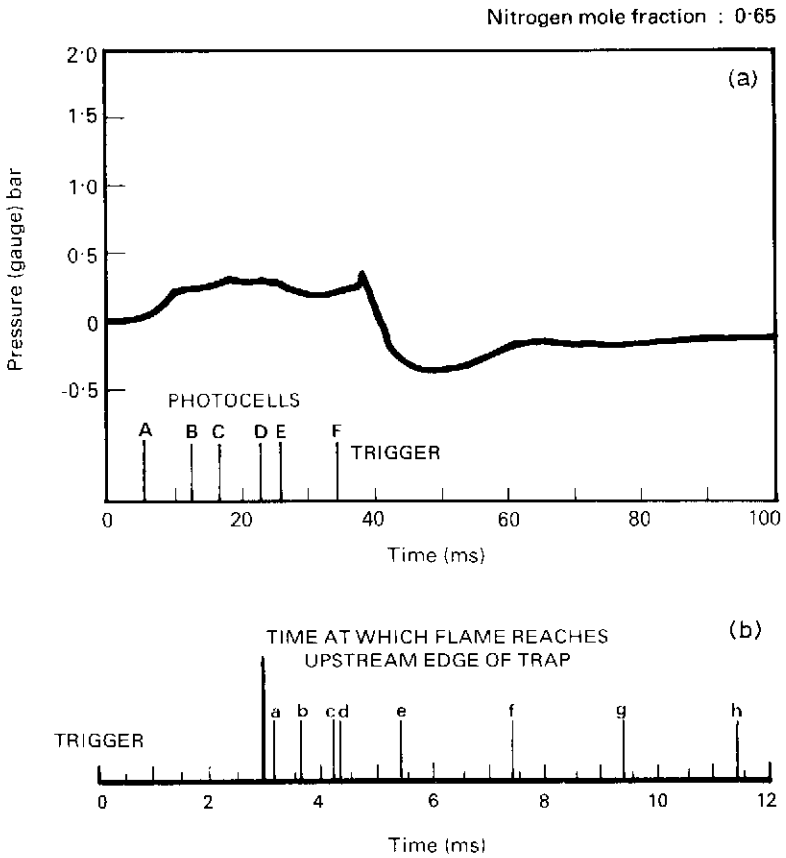

Fig. 4. Top: upstream pressure profile; bottom: time location of Schlieren photographs from Fig. 3.

either uniform across the view field or not, without any particular pattern. The photographs show that the hot combustion products and cold flammable mixture intermix in a plug of high intensity, small-scale turbulence, and suggest rapid stirring. The subsequent frames of Fig. 3 show the movement of the turbulent interface as burnt gas continues to flow through the trap. The high intensity of turbulence and fine scale of mixing are maintained throughout.

The intermixing will lower the temperature of the burnt gases and increase the temperature of the fresh flammable mixture. The effect of excessive intermixing of unburnt gas is apparent at the interface between the turbulent and undisturbed fluid. In the middle frames of Fig. 3 the intermixing appears to have substantially cooled the leading edge of the turbulent zone, a relatively low temperature gradient being suggested by a diffuse leading edge. By the later frames of Fig. 3, the interface has reached almost to the end of the viewing field. There has been substantial cooling and the leading edge of the turbulence has become very diffuse. Finally, the turbulence decays when the ejection of material from the trap comes to an end. Although unburnt material raised to an elevated temperature by intermixing must have undergone some reaction, the effect has not been sufficient to prevent cooling of the mixing zone and re-ignition has not occurred.

The final frame of Fig. 3 is taken approximately 8 ms after burnt gas first ejects from the trap. Initial ejection of hot gas occurs within 50 μs of the flame reaching the upstream edge of the trap. As the nitrogen mole fraction is decreased, giving more reactive mixtures, the flow field remains essentially as shown in Fig. 3.

However, when a nitrogen mole fraction of 0.59 is used the upstream pressure has increased substantially. Also, downstream pressure—time measurements show some oscillation and an increase in pressure. Figure 5 shows the Schlieren photographs for a nitrogen mole fraction of 0.59, and the pressure—time curves are shown in Fig. 6. The downstream edge of the trap has been moved into the viewing field at the extreme left-hand side of Fig. 5 and the flow structure immediately downstream of the gaps is shown. In frame (a) of Fig. 5 separate jets leave the gaps and merge a short distance from the downstream edge of the trap. The merging of the jets is not regular; in some cases the jets are disposed to bend towards each other rather than maintain parallel flow. This bending is typical of jets that are in close proximity to one another and is a result of the rapid entrainment of quiescent material between the jets. The jets in frame a are compressed unburnt gas which is rapidly cooled to ambient temperature by intermixing of fresh flammable material. The jet structure is evident, but is not as clearly distinguished once combustion products are being ejected.

Increased upstream pressures mean that the initial velocity of burnt gas ejection is increased and that there is more burnt material to flow out. The temperature of the burnt gases increases as the fuel—gas mixture becomes more reactive. Higher velocities must increase the intermixing of

fresh gas mixture, lowering the probability of re-ignition in a given situation because of greater cooling, but higher burnt gas temperatures and increased reactivity of intermixed material must increase the probability of re-ignition.

A nitrogen mole fraction of 0.59 is the most reactive mixture that lies on the non-ignition side of the boundary between non-ignition and re-

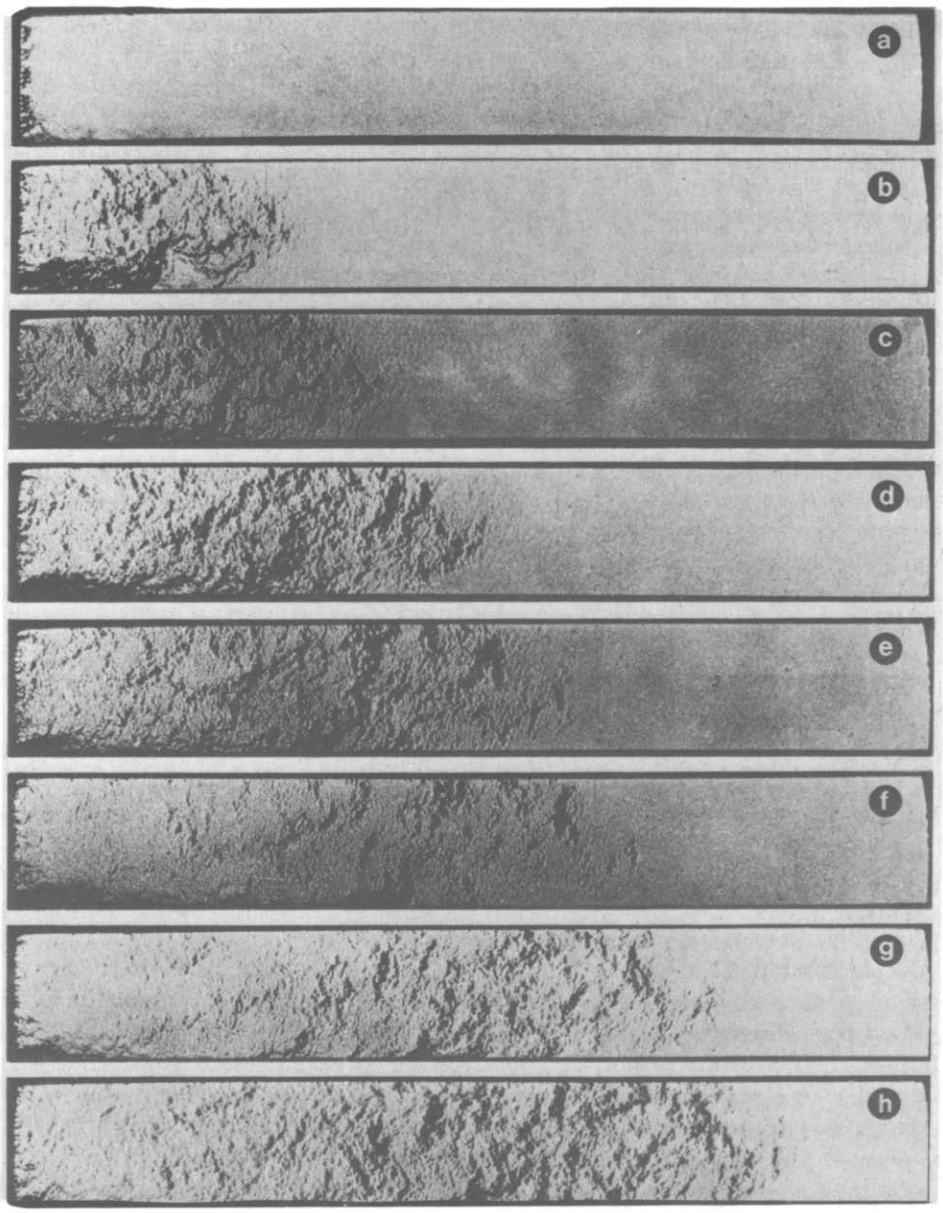

Fig. 5. Schlieren photographs for a nitrogen mole fraction of 0.59.

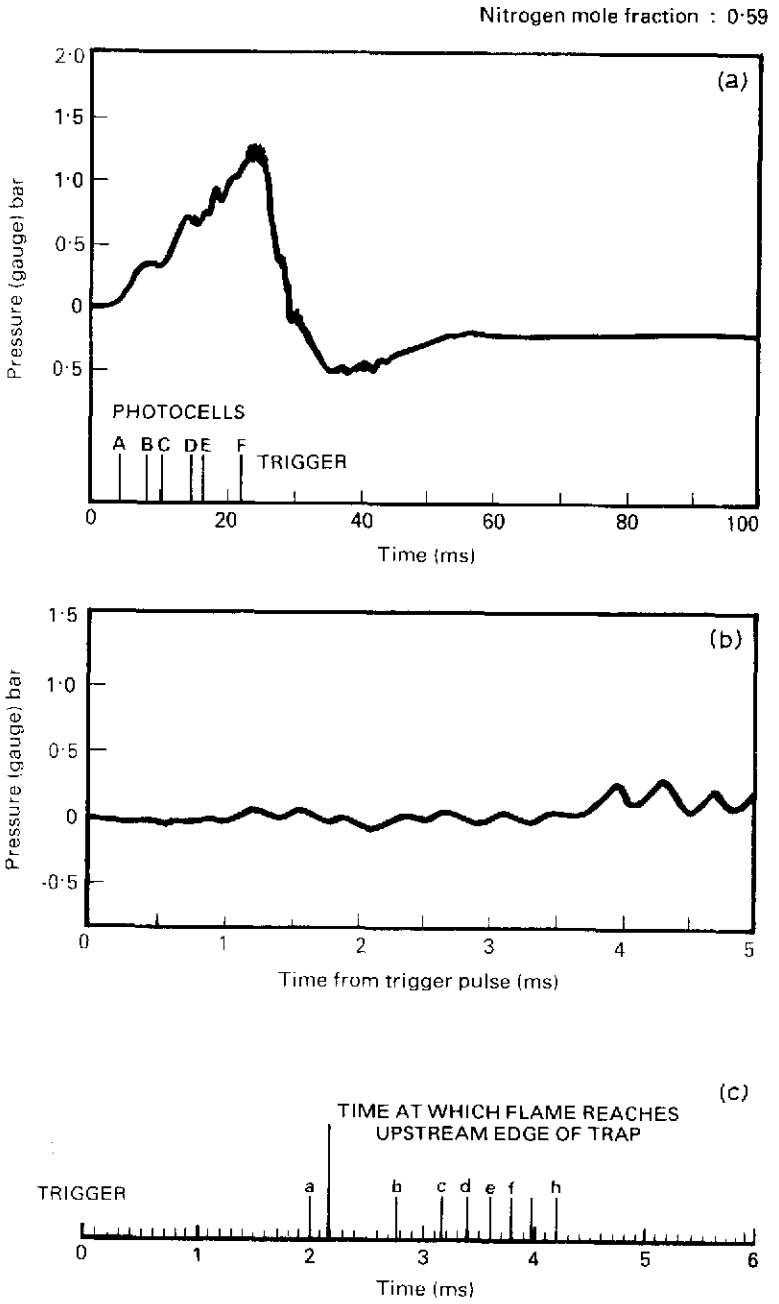

Fig. 6. Top: upstream pressure profile; centre: downstream pressure profile; bottom: time location of Schlieren photographs from Fig. 5.

ignition. As in other non-ignition experiments the leading edge of the turbulent intermixing region is diffuse, suggesting a low temperature and relatively high concentration of unburnt material. The later frames of Fig. 5 show that the material well behind the leading edge is turbulent, but appears relatively homogeneous compared to material further ahead in the turbulent plug, probably consisting mainly of burnt gas with little intermixed material. The most favourable conditions for re-ignition are found where a relatively large concentration of unburnt material occurs at a relatively high temperature. The photographs suggest that these conditions are found some distance behind the leading turbulence edge where fine-scale inhomogeneities in the flow field indicate fine-scale intermixing of fresh unburnt material and burnt gases. Here there is neither excessive cooling by entrainment, nor insufficient entrainment to allow reactions to accelerate. At a nitrogen mole fraction of 0.59 the conditions are not suitable for ignition, but at a nitrogen mole fraction of 0.58 downstream re-ignition does occur.

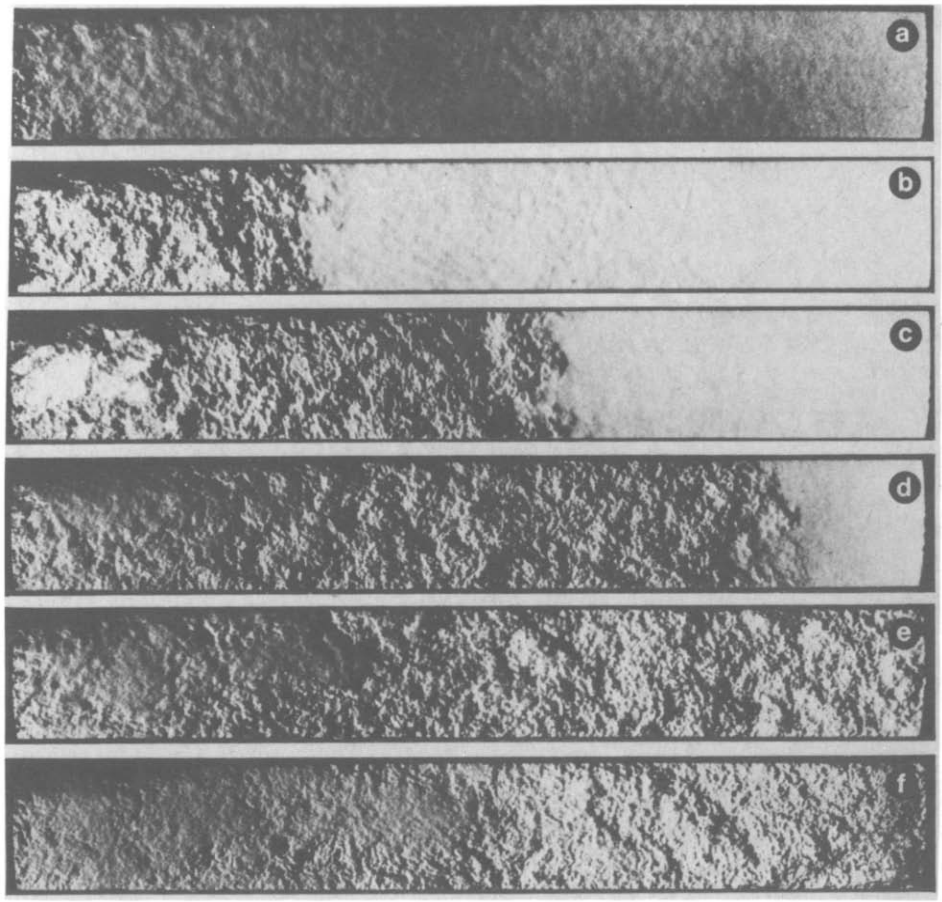

Fig. 7. Schlieren photographs for a nitrogen mole fraction of 0.58.

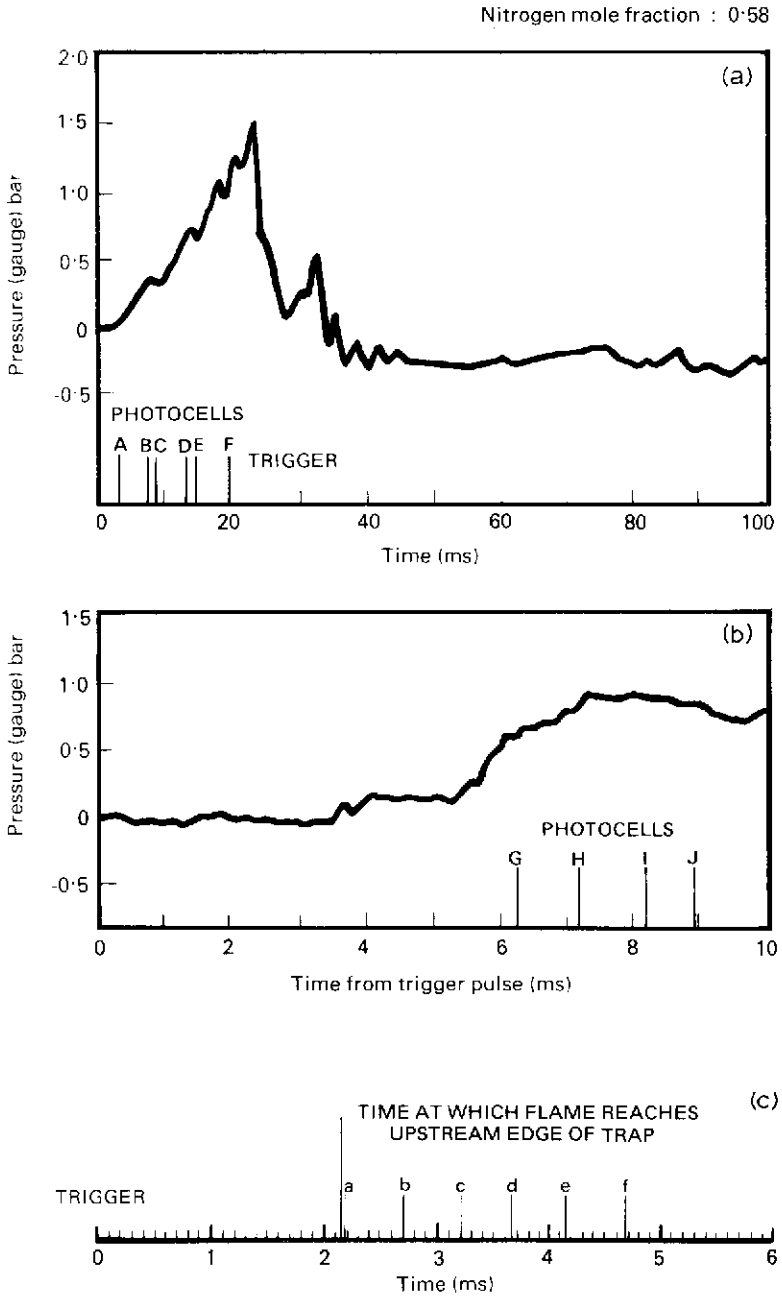

Fig. 8. Top: upstream pressure profile; centre: downstream pressure profile; bottom: time location of Schlieren photographs from Fig. 7.

The sequence of events on the ignition side of the non-ignition—ignition boundary can be seen in Fig. 7. The corresponding pressure—time profiles are given in Fig. 8. Figure 7, frame (a) shows compressed unburnt gas flowing out of the trap. Immediately after ejection of the burnt gases the turbulent mixing region is no different from that in a non-ignition situation. The usual turbulent regions are evident, and in frame (c) there is no indication of reaction, ignition or combustion. However, 500 μs later there has been formation of some combustion products inside the mixing zone well behind the leading edge and approximately 1.6 ms before a substantial downstream pressure rise (Fig. 8) which indicates flame propagation proper. The newly formed combustion products are indicated by relatively flat areas within the fine-scale structure of the turbulence zone that do not appear in non-ignition situations. Frame (d) of Fig. 7 does not show flame propagation; the leading edge of the turbulent zone is too diffuse, untypical of a propa-

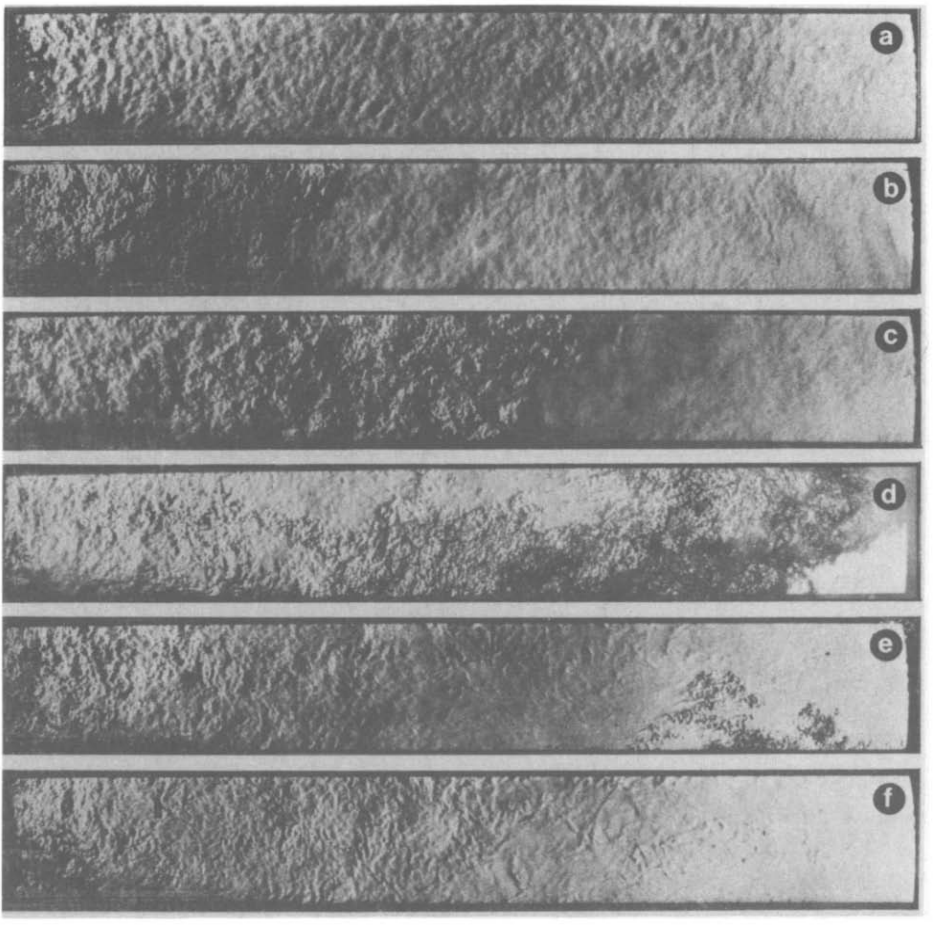

Fig. 9. Schlieren photographs for a nitrogen mole fraction of 0.56.

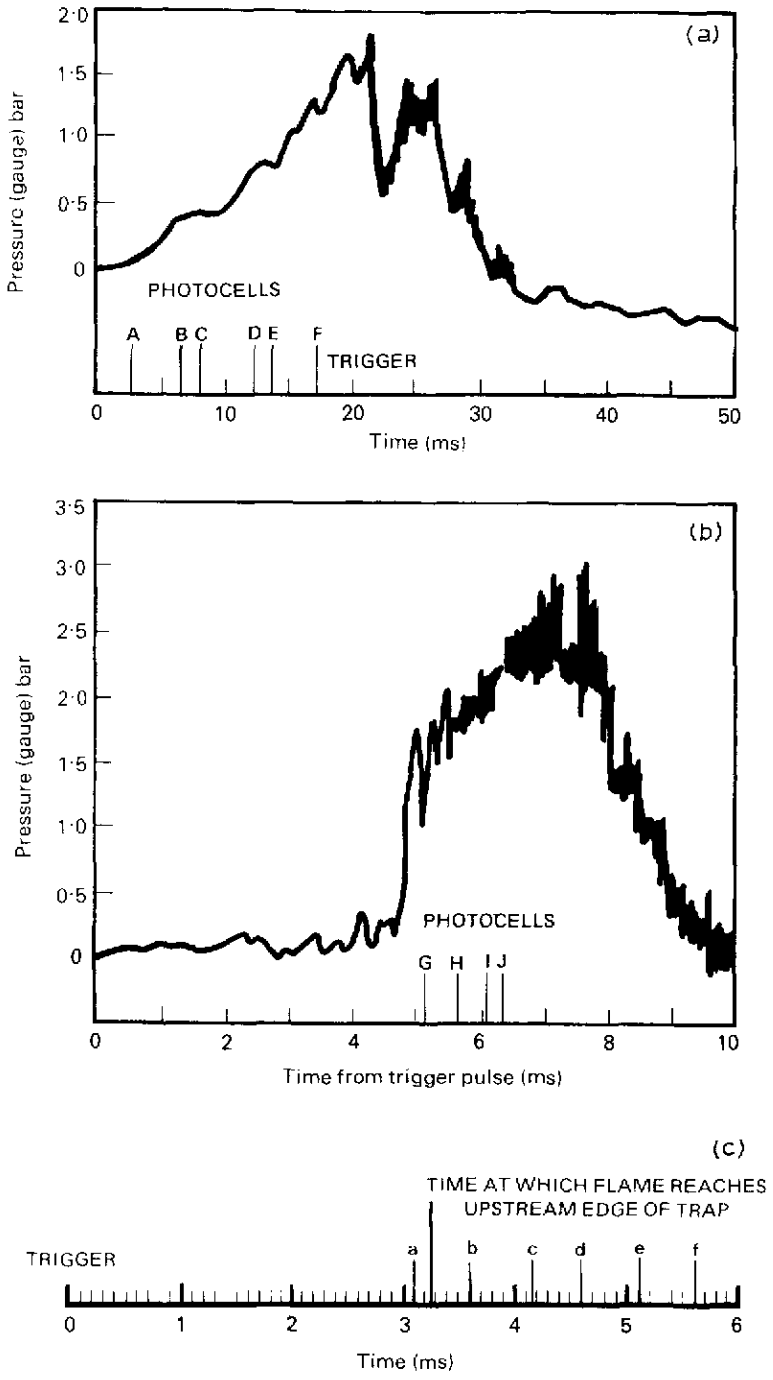

Fig. 10. Top: upstream pressure profile; centre: downstream pressure profile; bottom: time location of Schlieren photographs from Fig. 9.

gating turbulent flame and of the later stages of re-ignition. In the relatively unreactive conditions of Fig. 7 the development of combustion products from the intermixed material is relatively slow. The development of a propagating flame as evidenced by the downstream pressure rise in Fig. 8 occurs 0.5 ms after the final flame of Fig. 7. The slowness of the re-ignition sequence is typified by the pressure rise.

As the nitrogen concentration is further decreased the reaction rate increases, the flame that develops becomes more rapid and violent, and the downstream pressure rise becomes more abrupt. Figures 9 and 10 show results for a nitrogen mole fraction of 0.56.

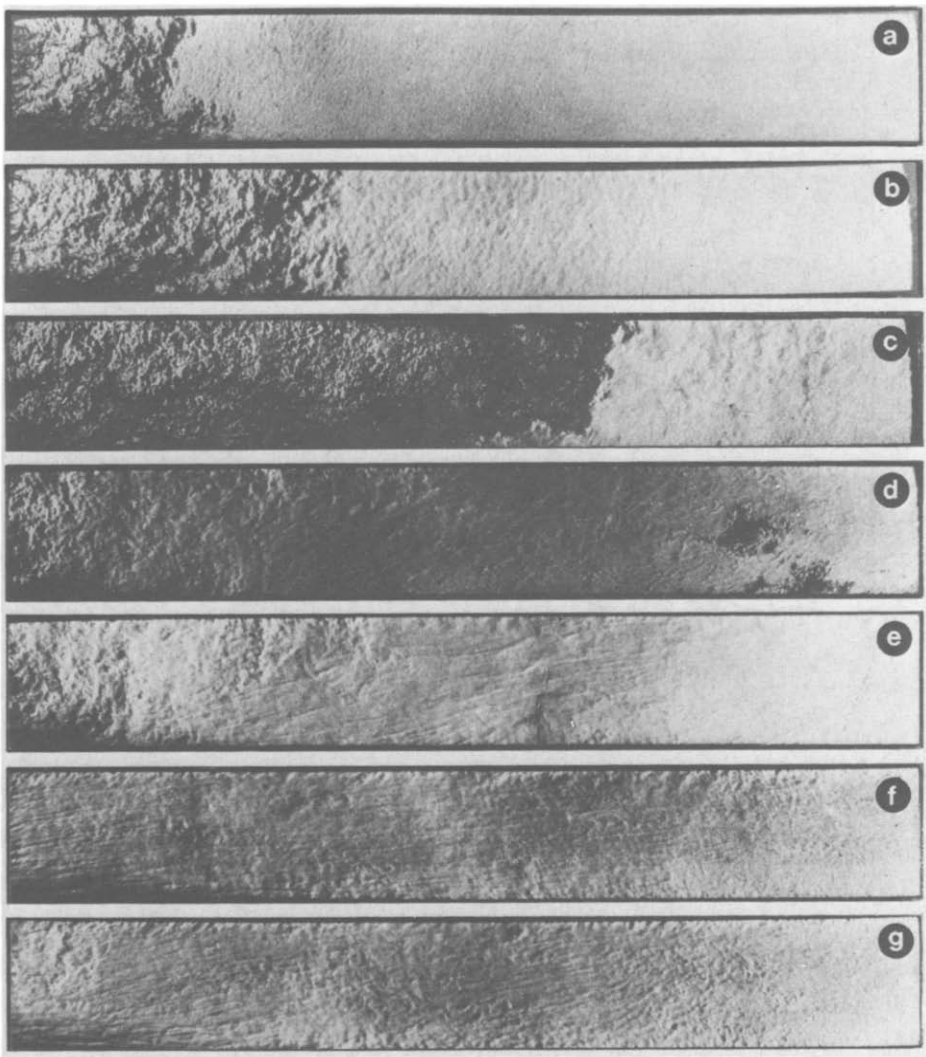

Fig. 11. Schlieren photographs for a nitrogen mole fraction of 0.54.

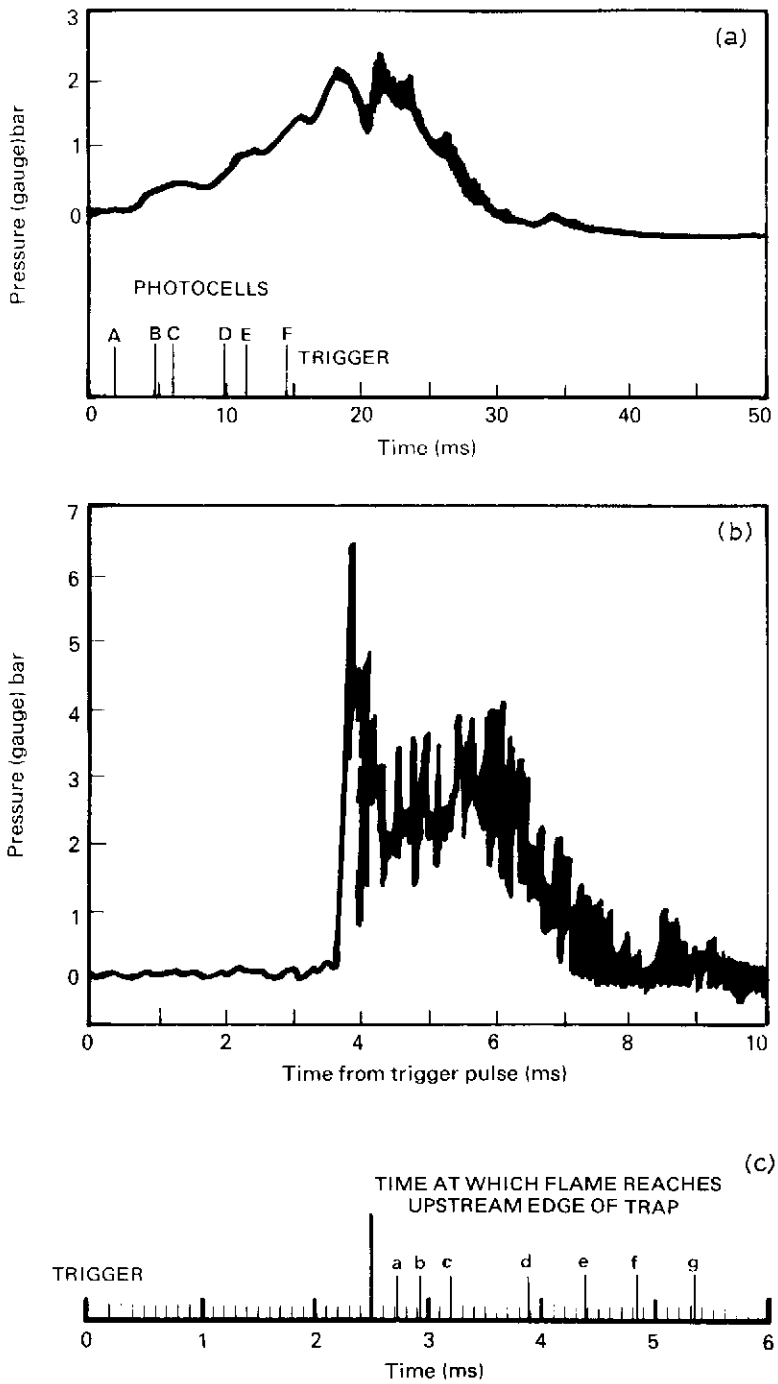

Fig. 12. Top: upstream pressure profile; centre: downstream pressure profile; bottom: time location of Schlieren photographs from Fig. 11.

Burnt gases eject from the trap, as before, and a turbulent mixing zone proceeds along the viewing field without any indication that re-ignition may occur. By frame (d) of Fig. 9, however, the ignition sequence is well developed, burning is taking place at the midpoint of the viewing field and combustion products are forming at some distance behind the leading edge. Ahead of these combustion products is a zone of fine-scale turbulence where a transition towards the self-propagating flame that will outrun the purely mixing interface will be occurring. The abrupt downstream pressure rise, which indicates the flame travelling along the duct, occurs 100—200 μs after frame (d), so although combustion can be taking place in the turbulent plug, and a high-temperature reacting zone can be in close proximity to fresh flammable gas, there is a delay of a few hundreds of microseconds before a self-propagating flame is formed.

In succeeding frames, (e) and (f), combustion has passed on and in the viewing field there remains an eddying residue of burnt gas with isolated pockets of burning material which are eventually consumed. Material is still being ejected from the trap as the continuing turbulence around the trap exit indicates.

Figure 11 shows the results of a nitrogen mole fraction of 0.54; the associated pressure—time curves are given in Fig. 12. Frame (c) is at an earlier stage in the ignition sequence than frame (d) of Fig. 9. Here the combustion products are only just forming and it is some 400 μs before a self-propagating flame causes an abrupt pressure increase. However, although the interface maintains a diffuse character, it appears somewhat sharper than previously, indicating an increasing temperature gradient across it. Five hundred microseconds later, in frame (e), combustion has essentially left the view field. The turbulence close to the trap vanishes about 1 ms after the abrupt downstream pressure rise and at approximately the same time an upstream pressure rise is registered, due to material being forced back through the trap by the downstream explosion. In the final two frames of Fig. 11, material in the viewfield is moving towards the trap.

As the nitrogen mole fraction decreases further the same effects are noticed, but with more rapid combustion and re-ignition, sometimes leading to the formation of pressure waves in the downstream duct. At a nitrogen mole fraction of 0.52, the development of a self-propagating flame is once again delayed even though combustion in some parts of the turbulent plug has gone to completion.

Conclusions

Schlieren photography of the region downstream of a flat-plate flame trap shows that the burnt gas ejected from the trap combines with the fresh flammable mixture to form a highly turbulent mixing zone. This mixing zone behaves as a stirred reactor. If, under the most suitable conditions for reaction in the mixing region — i.e., relatively high temperature and

relatively high reactant concentration — the rate of cooling by intermixing of fresh material is insufficient to overcome the heating effects of reaction, re-ignition will occur. If, however, the rate of entrainment does overcome the effects of reaction, the temperature in the mixing zone will fall and no re-ignition will occur. The division between re-ignition and non-ignition corresponds to the blow-out condition in a stirred reactor. A self-propagating flame forms after a delay time. With gas mixtures at which the flame trap has only just failed to arrest the flame, the sequence leading to self-propagation is relatively slow, actual self-propagation occurring 1.5—2.0 ms after the first formation of downstream combustion products, but as the reactivity of the gas mixtures increases, the ignition sequence speeds up, although there are delays of several hundred microseconds between product formation and abrupt downstream pressure rise with the most reactive mixtures used in these experiments. During this delay, there occurs a close proximity between a high temperature region and fresh mixture, and finally, self-propagating combustion takes place. The visible formation of combustion products inside the mixing region is invariably followed by transition of a self-propagating flame.

References

1 W.B. Howard, Flame arresters and flashback preventers, Plant/Operations Prog., 1 (1982) 203—208.
2 S.A. Ames, J.P. Davies and Z.W. Rogowski, Performance of metallic foam as a flame arrester, Fire Research Note No. 809, Fire Research Station, Great Britain, 1970.