The Transition to Detonation from Deflagration in Ethylene–Oxygen Systems

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The flames of ethylene and oxygen mixtures (initial pressure, 50—500 mmHg, and ethylene content, 20—40%) were studied, especially for the transition to detonation from deflagration. The flames may roughly be divided into four groups: **A**, a flame without any shock wave generation; **B**, a flame with a shock wave generation; **C**, a flame with many shock waves and much turbulence of the flame, and finally **D**, the detonation produced by the collision of a flame and a reflected shock wave at the bottom of the tube. The flame transit to detonation from deflagration is a linear relation between the velocities of the flames at the point of detonation and DID, or the distance from the point of ignition to the detonation for all the sorts of flames given above, in spite of several apparent differences.

Since Berthelot and Vieille, and Le Chatelier and Mallard observed the propagation of detonation waves in 1881,[1)] numerous works on the velocities of detonation waves, the theory of the transition to detonation, *etc.* have been published.[2)] In the investigation of the transition to detonation, Payman and Titman observed the process using a streak schlieren photograph and discussed the mechanism of the onset of detonation.[3)] Later, Bone *et al.* and White and Martin[4)] investigated this process, while Oppenheim and his co-workers studied the transition processes in especial detail.[5)] They used the stroboscopic schlieren system with a laser light and observed the mechanism of the transition to detonation in hydrogen–oxygen systems, classifying the process into the following four sections: 1) the explosion in the vicinity of a flame front, 2) the action of a shock wave formed at the lip of a flame, 3) the ignition at a shock front, and 4) the shock merging ahead of a flame.

In the present investigation, the processes of the transition to detonation in ethylene–oxygen systems were studied and the factors involved in this transition were fully discussed.

Experimental

The experiments were performed with C_2H_4–O_2 mixtures, at an initial pressure of 50—500 mmHg, in a square, 4×4 cm cross section and a 162 cm-long detonation tube, fitted on both sides with optically flat 4×30 cm glass windows. The optical observations have been made by means of stroboscopic schlieren photographs. This observation was accomplished using 30 cm mirrors Z-type schlieren system, an argon stroboflash lamp, and a drum camera. The ignition was effected by means of a hot-wire glow coil.

Results and Discussion

In several mechanisms of the transition to detonation in flames, a detonation is generally produced by an explosion of the flame itself or is effected by means of a shock wave. In this study, four cases of transition to detonation were observed: **A**, without any shock wave generation; **B**, with a shock wave generation and a little distortion of a flame; **C**, with many shock waves, with much production of flame turbulences, and **D**, by the collision of a flame and a reflected shock wave at the bottom of the tube.

Figure 1 shows diagrams of the concentrations of the

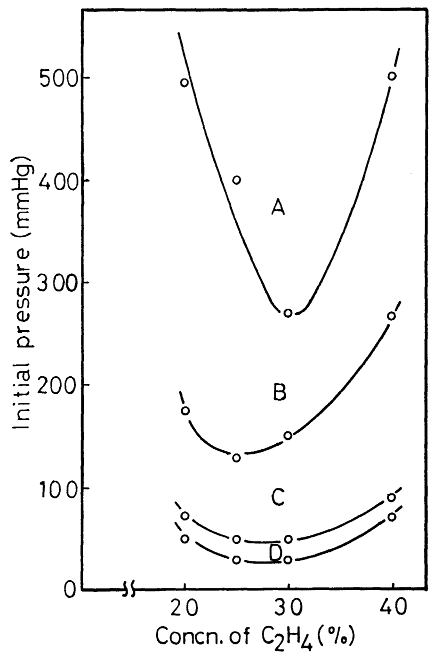

Fig. 1. Classification of propagation of flames.

ethylene *versus* the pressures of the total gas mixture in a 162 cm-long tube. The regions between curves are the ranges where flames of Type **A**, **B**, **C**, and **D** are found; Type **A** is generated very exceptionally.

In Fig. 2, a schlieren photograph of Type **A** is given. The flame has a dome shaped flame front until the region of the transition to detonation, without any sign of turbulence ahead of the flame. The surfaces of the flame are not uniform, but are blurred before the onset

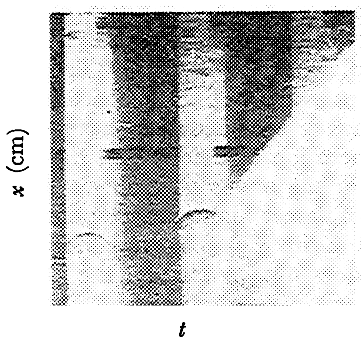

Fig. 2. Schlieren photograph of flame, type A.
x: Distance from ignition point, t: 25 μs/frame.

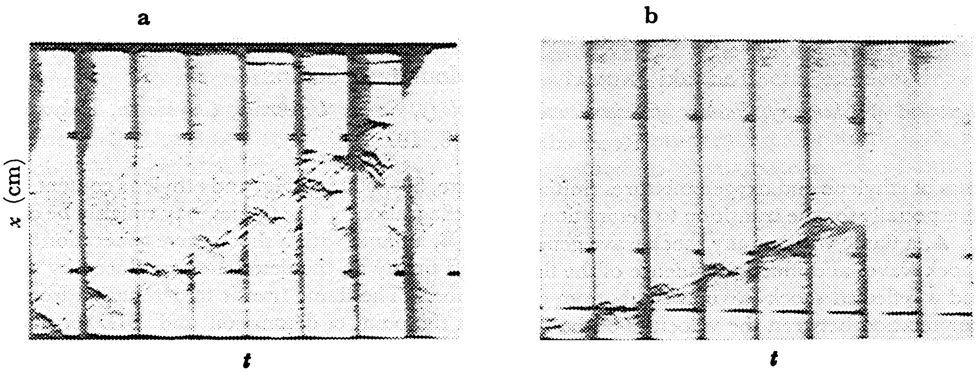

Fig. 3. Schlieren photograph of flame, type C.
x: Distance from ignition point, t: 25 μs/frame.

of detonation; this may be attributed to the cellular structure, or the local explosion started at a flame front with a high temperature and a high pressure conveyed from the reaction part. The only difference between the **A** and **B** types is the generation of shock waves. If shock wave is generated in Type **B**, the shock wave is very weak and cannot generate the detonation. Therefore, the transition to detonation occurs in a similar way in Types **A** and **B**.

Type **C**, depicted in Fig. 3, is most frequently observed. The four mechanisms reported by Oppenheim *et al.*[5] and mentioned above are also of this type. A detonation wave starts at a flame front or immediately ahead of a flame, as is shown in Fig. 3. In this type, the state of a flame front and the unburned mixture ahead of a flame change every time. Two forms of the onset of detonation are observed, one at the shock wave generated at the lip of a flame front (Fig. 3-a), and the other, in the vicinity of a flame front (Fig. 3-b).

The transition to detonation is essentially connected with the initial pressure of the gas mixture and the mixing ratio of the composition. Besides these, the detonation induction distance, DID, or the distances from the ignition of a flame to the point of detonation *versus* the initial gas pressures of mixture are shown in Fig. 4. The curves decrease against the pressures of the initial gas mixtures and approach constant values over 300 mmHg. These values seem rather small compares with the values which has been cited for hydrogen–oxygen,[6] methane–oxygen, and acetylene–oxygen[7] by other investigators, who have all reported constant values of a few atmospheres.

As DID change its value according to the values of the tube diameters and the condition of the tube wall, one can hardly expect constant values to be determined by, for example, initial pressures. Therefore, the absolute numerical values of these constants have not so much meaning as they seem to have.

For the generation of detonation, the turbulences of a wave front or the onsets of shock waves which make the velocities of flames higher are responsible; therefore, Types **B** and **C** in Fig. 4 correspond in these cases, but Type **A** does not. Actually, the DID of Type **A** does not concern initial pressures in higher region than a certain value, and consequently there is no effect on the state after the flame begins to move and there is still detonation. Therefore, the phenomena, such as

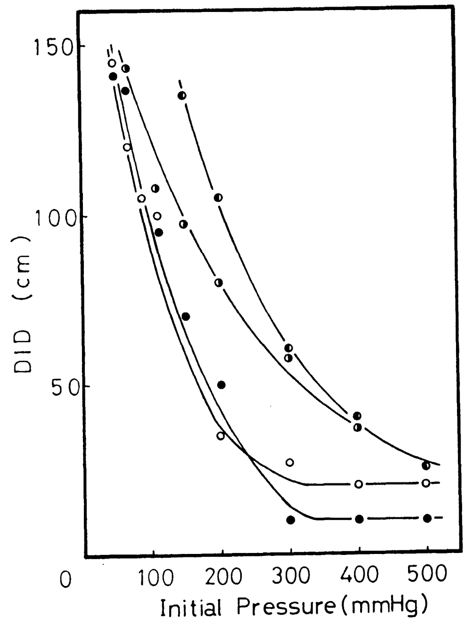

Fig. 4. Detonation induction distance of ethylene-oxygen mixture.
◑: 20% C_2H_4-80% O_2, ○: 25% C_2H_4-75% O_2,
●: 30% C_2H_4-70% O_2, ◐: 40% C_2H_4-60% O_2.

the turbulence of a flame or a shock wave after a flame begin to propagate, may not necessarily always be responsible for the onset of detonation. Presumably an ignition energy of Type **A**, which maintains the system at the beginning, may be enough for the detonation.

Now the definite conditions, other than shock waves and turbulence, for which the detonation is responsible, can be considered. Figure 5 shows the relation of DID *versus* flame velocities immediately before the onset of detonation. The graph is linear for all sorts of flames at pressures of 70—500 mmHg and at compositions of the gas mixture of 20—40% ethylene, independent of the generation of shock waves or the turbulence of the flame. The flame which transits to detonation must have, at the very point of detonation, a definite value of a flame velocity. The flame in Type **A** which has enough flame velocity without any support of turbulence, transits to detonation by itself, while Types **B** and **C**, the velocities of which are insufficient to reach detonation, must get the support of turbulence of a flame to

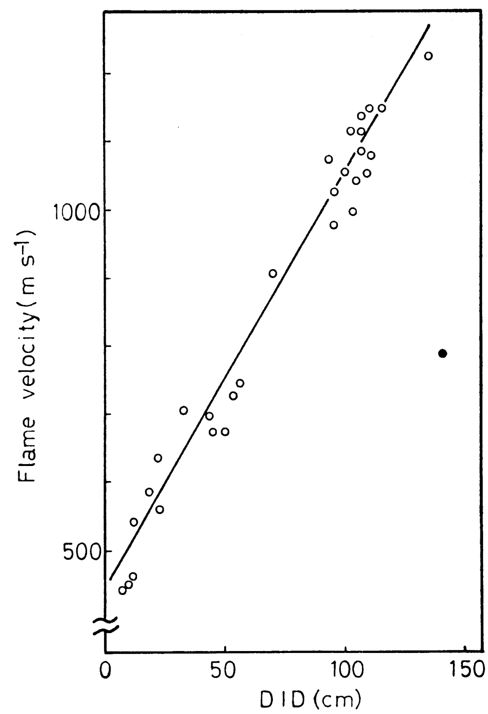

Fig. 5. Flame velocity at the detonation point.
○: Without the collision of reflected shock waves,
●: with the collision.

make the velocities higher. Thus, the velocity of the flame at the point of detonation is the largest factor in the detonation.

In Fig. 5 there is one point (the dot on the right of the diagram) which is outside the curves and which belongs to Type **D**. Figure 6 shows a typical example of this type. In Type **D** the detonation wave is generated after the collision of a flame and a reflected shock wave. The point outside the diagram in Fig. 5 does not contradict the theory. After the collision, the flame propagates in the region of higher pressures and higher temperatures, and the particle velocity becomes nil. If the tube is longer or the collision of a flame and a reflected shock wave does not occur, the dot in Fig. 5 will shift and find itself on the elongation of

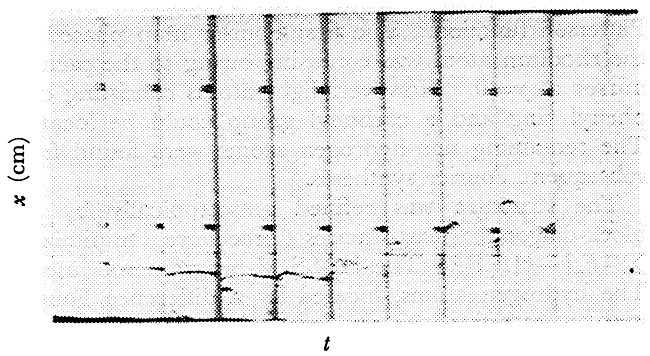

Fig. 6. Schlieren photograph of flame, type D.
x: Distance from ignition point, t: 25 μs/frame.

the straight line. In Type **D**, just before the detonation the turbulences in both the unburnt gas and the flame are less and the velocity of flame is slower than in Type **C**. Therefore, in Type **D** the detonation will be aroused through the collision of a flame and a reflected shock wave. After the collision, the flame propagates through the region of higher pressures. The value of this pressure, according to the theory, is 420 mmHg (observed 460 mmHg), and the velocity of flame at the point of the collision is 760 m s^{-1}. In Fig. 5, if the initial pressure is 460 mmHg, then the flame of 550 m s^{-1} is detonated and in Fig. 6 the actual flame velocity of 760 m s^{-1} will have enough energy for the detonation. Thus, the point of the dot in Fig. 5 elucidates the generation of detonation.

Another example is the initial gas flame of the pressure of 30 mmHg, which cannot be detonated by the collision of a flame and a reflected shock wave. The observed pressure of the reflected shock wave is 230 mmHg, the observed velocity of the flame is 510 m s^{-1} and the acceleration of the flame and the velocity of the shock wave are very similar to the flame of 50 mmHg. The flame with the initial pressure of 230 mmHg will be detonated with the flame velocity of 650 m s^{-1}, which can also be concluded from the theory. Therefore, if the flame is accelerated for some 10 m s^{-1} before the collision on the bottom plate, then the flame will detonated, but the flame collides with the plate, before that and will not be detonated with enough energy. Thus, in Type **D** the transition from the deflagration depends on a flame velocity which gains from the collision of the flame and the reflected shock wave.

At any rate, the velocity of the flame at the point of detonation and the DID are the predominating factors for the phenomena of the transition to detonation from deflagration, with or without any collision of a flame and a reflected shock wave.

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