Flame Velocity for the Onset of Detonation

Tadaaki Inomata,* Satiko Okazaki,† Takao Moriwaki,† and Momotaro Suzuki†
Sophia University, Tokyo, Japan

Of interest in this study was the collision of a flame with a shock wave emitted from the flame itself and propagated in the opposite direction to the flame after reflection at the end of a combustion tube. The transition to detonation occurred at a critical initial pressure for various tube lengths. It did not begin below a certain limit of the flame velocity at the collision point and it occurred with no stimulus from the reflected shock wave beyond a critical flame velocity. Relations between the detonation induction distance and the minimum flame velocity leading to the detonation and relations between the flame velocity at the collision point and the distance from the collision point and the detonation point are presented.

Introduction

IN a fire within a structure or a factory, the transition from combustion to detonation may cause damage not only to the building itself but also to the surrounding area. It has been noted that the interaction of a flame with a shock wave induced by the flame, especially the head-on collision between the flame and the flame-generated shock wave reflected at a solid front wall, contributes to the flame acceleration and leads to detonation. Thus, it is important to observe such collisions in a tube as part of the basic research into the prevention of disasters caused by such combustion.

Since confirmation of the existence of detonation waves, many studies have been made on the onset of detonation (e.g., see Refs. 1-3). Oppenheim and Urtiew[1] observed four causes of detonation.[1] But their study did not discuss whether the collision of a flame with a reflected shock wave, one generated ahead of the flame and propagating in a direction opposite to the flame after reflection at the end plate of a tube, was involved in the generation of detonation.

The process of interaction between a flame and a pressure or shock wave has been investigated both theoretically and experimentally. Markstein[4] treated the head-on collision between a laminar flame and a shock wave generated in a shock tube and concluded that the acceleration of a laminar flame and vibrating combustion were explained by the Taylor instability.[5] Leyer[6] analyzed the effects caused by a pressure wave emitted by a flame propagating in a closed tube in an attempt to explain the vibratory phenomena. He showed that an understanding of how fresh gases move could be used to interpret the vibratory movement of the flame. Oppenheim and Urtiew[7] observed the interaction between a shock wave ahead of a flame and a secondary transverse flame ignited at the side wall of a tube; they indicated that the velocity of shock wave, Mach 1.7, was too low for the onset of detonation. However, these investigations used a laminar flame and waves which were generated by supplementary methods rather than directly by the flame.

On the other hand, Payman and Titman[8] have reported that if the shock wave was intense enough, then upon propagating to the end of the tube, it would not only ignite the gas mixture but also instantaneously initiate the detonation therein. If the shock wave was weak and not powerful enough to ignite the gas it would collide with the flame after reflection at the tube end and this collision would cause a temperature increase sufficient to initiate detonation at the flame front. White and Martin[9] and Inomata and Suzuki[10] observed the same phenomena. Salamandra and Sevastyanova[11] studied the collision between a flame and a reflected shock wave in order to determine the increase in the intensity of the shock wave but they did not observe the transition to detonation. Evans and Ablow[12] have stated that compression waves reflected at the end of a tube appeared to accelerate the flame velocity and to promote combustion. However, the transition to detonation by the head-on collision of a flame with a reflected shock wave emitted by the same flame has not been investigated systematically.

The purposes of the present research were to observe the details of the generation of a detonation wave through such a collision and to obtain some information about the conditions of detonation initiation by controlling the energies of the flame and the shock wave by the variations in the initial pressures of the gas mixture and in the lengths of the tube.

Experimental Setup

Gas mixtures of 25% ethylene-75% oxygen with initial pressures of 5.33-53.3 kPa were used. Combustion tubes, similar to those in Ref. 10, were one to four pieces of 4 × 4 cm cross-section and 42 cm long tubing which were combined as required. An ignition plug and end plates of various thicknesses resulted in a total length of 34.5, 78, 120, and 162 cm. A set of 4 × 30 cm optical windows enabled strobo-schlieren photographs to be taken. These parts were carefully constructed to assure smooth inside walls. Z-type schlieren apparatus, an argon stroboflash lamp, and a drum camera were used to observe the phenomena. Triggering of the lamp was effected by means of a phototransistor which detected the light of a flame. Ignition was performed by a nichrome wire device with a 6 V ac source.

Results and Discussion

In tubes of various lengths, gases of ethylene-oxygen mixtures with different initial pressures were introduced and ignited at the end of the tube. Under certain experimental conditions, in the course of the propagation of a flame, a shock wave may be generated, reflected at the far end of the tube, and then collide with the flame.

Figure 1 depicts the relation between the lengths of the tube and the initial pressures. The region above the upper curve is the zone where the detonation occurs without any collision of the flame with the reflected shock wave, and that below the lower curve is the zone where no detonation occurs even with a collision. Between the two curves is the zone where the detonations through collision occur. The region is broader in shorter tube lengths and, in tubes longer than 162 cm, the difference between these two curves may not be discernible. Various measured values are summarized in Table 1.

Detonation does not occur immediately after the collision; actually the detonation can be seen 25-200 μs after the

Received March 29, 1982; revision received Aug. 10, 1982.

*Lecturer, Department of Chemistry.
†Professor, Department of Chemistry.

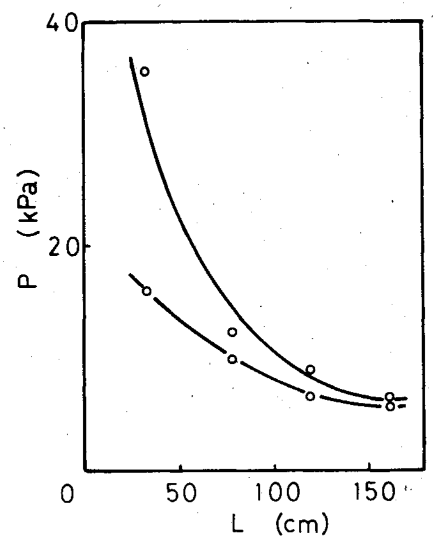

Fig. 1 Detonation limits for initial pressure P and tube length L.

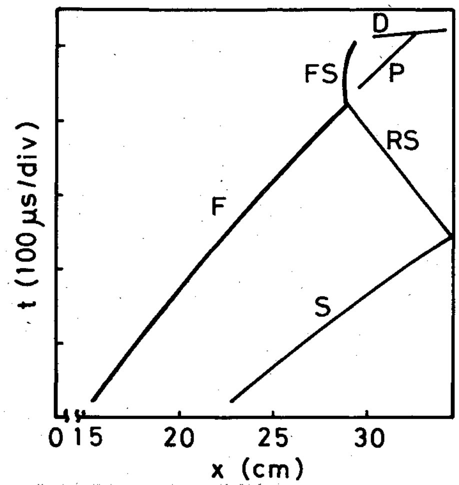

Fig. 2 x-t diagram of the collision of a flame with a reflected shock wave (17.3 kPa initial pressure).

collision. The x-t diagram of a flame in a tube 34.5 cm long is shown in Fig. 2. After the reflection at the end wall, the shock wave with uniform velocity (symbol RS) collides with the flame (symbol F) coming from the opposite direction. The flame is propagating at a small acceleration before collision with the shock wave. By the time of collision the reflected shock wave and the flame together form a plane wave (symbol FS). Finally, the new pressure waves (symbol P) and the FS wave develop into a detonation wave (symbol D). The situation was almost identical for all other collisions leading to detonation, but the numerical values of velocity and acceleration differed. If the tube is long enough and a flame produces a detonation wave before colliding with a reflected shock wave, the distance from an ignition plug to a detonation point (DID) reached 30-90 cm under the initial pressures shown in Table 1. Therefore, the DID is shortened by the collision in the 34.5 cm tube.

In the 78 cm long tube, the interaction phenomena of a flame and a reflected shock wave are very complicated. A detonation wave is formed at the flame front or behind the new shock wave produced by the collision. In the 120 cm tube, two or three subsequent shock waves are generated and at the time the detonation wave is generated the flame front vanishes after collision. In both tubes, the DID is considerably shortened by the collision: to 72-76 cm with collision from 100-120 cm without collision in the 78 cm tube and to about 112 cm from 140-170 cm in the 120 cm tube.

In the longest tube (162 cm) the situation was as simple as in the 34.5 cm tube. Because of the extremely narrow region of initial pressure, shown in Fig. 1, the flame velocity and the collision point in this tube could not be controlled as desired. As a result, the DID without the collision was not observed directly. However, it is clear that the DID in this longest tube is also shortened by the collision of a flame with a reflected shock wave. While the minimum flame velocity needed to generate the detonation wave without collision when the DID was 144 cm was 1300 m s^{-1},[10] the flame velocity with collision was only 790 m s^{-1} at the same DID. If the collision of a flame with a reflected shock wave does not contribute to the onset of detonation, the flame in this experiment cannot generate the detonation wave at 144 cm from the ignition point and the DID value should be considerably longer than 144 cm in this flame.

Obtained in four tubes, these facts indicate that the collision of a flame with a reflected shock wave significantly contributes to the transition from deflagration to detonation.

Although burning pockets generated by the head-on collision lead to the onset of detonation, all of the phenomena in this study cannot be interpreted in the same manner. At least two mechanisms of the transition to detonation were observed: one is an autoexplosion in the burning pocket; the other is an ignition behind a new shock wave produced by the collision, whose presence is confirmed by the vanishing of the flame front or the existence of the flame at the time of the onset of detonation. Phenomena such as these have generally been explained by the Taylor instability.[5] According to the modified Taylor instability,[4] the acceleration of a flame in the backward direction after collision with a reflected shock wave should cause the flame to stabilize or the flame front to deform in a direction opposite to the flame propagation in this experiment. Consequently, the flame accelerated in the backward direction in Fig. 2 should be stabilized; however, the distortion of the flame surface, which increases with time after interaction, may lead to a local explosion of the gas mixture and result in the onset of detonation. At the same time, however, the increase in the volumetric burning velocity will cause the emission of pressure waves. If intense enough, an ignition may occur behind these waves and lead to detonation. Because the detonation began in front of the FS complex shown in Fig. 2, the latter explanation is more reasonable than that citing a local explosion of the gas

Table 1 Various values to generate a detonation by the collision of a flame with a reflected shock wave

Tube length, cm	Initial pressures, kPa	Velocities of the first reflected shock waves,[a] m s^{-1}	V_c, m s^{-1}	Collision point,[b] cm	DID, cm
34.5	16.0-37.3	270-350	370-490	27-29	28-30
78	9.87-12.0	290-340	540-840	65-74	72-76
120	6.67-8.67	300-350	700-1170	101-107	108-118
162	6.40-6.67	~310	~800	141-143	144-146

[a]Values immediately after reflection at the end of wall of a combustion tube. [b]Distances from an ignition plug. V_c = flame velocity at the instant of collision of a flame with a reflected shock wave. DID = detonation induction distance.

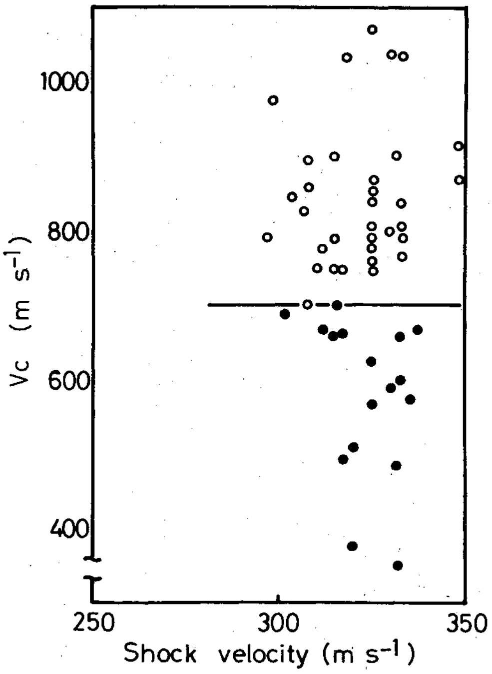

Fig. 3 **Relation of V_c and reflected shock-wave velocity immediately after reflection (○ = detonation; ● = no detonation). V_c = flame velocity at the instant of collision of a flame with a reflected shock wave.**

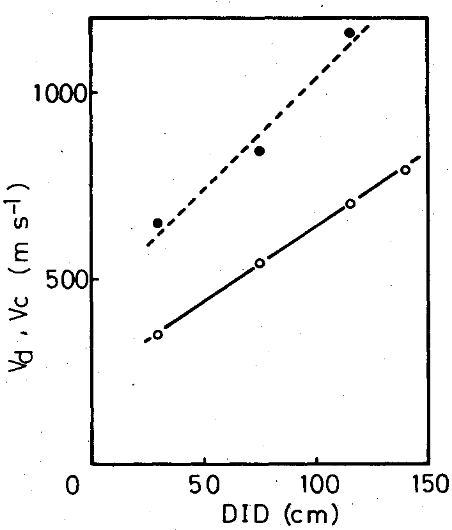

Fig. 4 **Lowest and highest V_c vs DID values in four tube lengths. V_c = flame velocity at the instant of collision of a flame with a reflected shock wave; DID = detonation induction distance.**

mixture. The former mechanism appeared primarily in the 120 and 162 cm tubes.

It is interesting to note that the lowest boundary of the flame velocity V_c at the instant of collision which generates the detonation wave is constant at 700 m s^{-1}, in spite of various shock-wave velocities in the 120 cm tube (Fig. 3). In Fig. 4 both the solid straight line and open circles relate to the lowest V_c and the DID measured in four tubes. The solid circles show the flames with the highest V_c and the dotted line shows the relationship between the flame velocity V_d at the detonation point and the DID which was shown to be required to produce a detonation wave without a collision[10]; the two sets of data agree well. These facts mean that a certain value of V_c is necessary for the collision to generate a detonation; the increase in the flame velocity needed for the onset of detonation is in proportion to the increase in the distance from an ignition plug; and the flame having the highest V_c must have enough energy to cause the transition to detonation

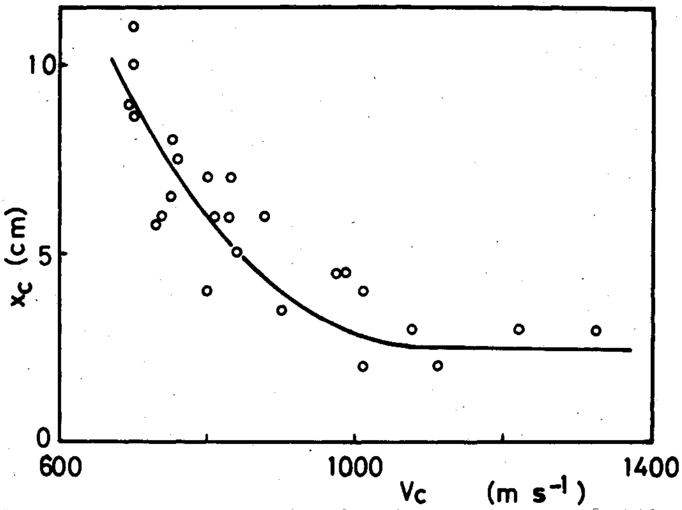

Fig. 5 **Relations between V_c and x_c in 120 cm tube. V_c = flame velocity at the instant of collision of a flame with a reflected shock wave; x_c = distance from the collision point to the detonation point.**

by itself. V_c reflects both the laminar flame velocity and the mass motion of the gas in front of a flame. A fame emits pressure waves or shock waves in succession through the propagation. These waves lead to variations in temperature, pressure, and density, namely, the laminar flame velocity as well as the gas velocity in front of the flame. Moreover, a flame velocity V_c must result from an initial pressure, condition of the tube wall, and dimension of a combustion tube, in addition to the velocities mentioned above. Therefore, it is reasonable to assume that V_c is the key parameter in establishing the transition to detonation as the overall result of these effects.

Another interesting relation is that between the flame velocities and the distances from the collision point to the detonation point, x_c. This could be observed in each tube, as shown in Fig. 5 (120 cm tube). According to a simplified calculation, DID was inversely proportional to the temperature of the unburned gas.[13] At the time of collision of a flame with a reflected shock wave, the flame begins to pass through the high-temperature region behind the reflected shock wave; this means that the temperature suddenly rises. Velocities of the pressure[14] and shock waves[15] that is, the temperature of the unreacted gas—increase with increasing flame velocity. After reflection at the end wall of the tube, the first shock wave interacts with other pressure or shock waves propagating in the opposite direction. Therefore, the temperature behind the reflected shock wave at the collision point with a flame must increase with increasing flame velocity, in spite of the almost constant velocity of the first shock wave immediately after the reflection at the tube end. Consequently, x_c becomes short with increasing flame velocity, even if the turbulence does not significantly increase, as in the 120 cm tube.

In addition to the experimental fact that a long DID requires a rapid flame velocity for the onset of detonation, various factors making the DID short (namely, turbulence, normal burning velocity, and roughness of a tube wall) lead to flame acceleration. Thus, the flame acceleration may be a macroscopically good indicator of the transition to detonation. In this study, the minimum flame acceleration corresponding to the solid line in Fig. 4 was about 2.4×10^5 m s^{-2} except for the 34.5 cm tube (3.1×10^5) and the maximum acceleration (solid circles in Fig. 4) was 4.7×10^5 m s^{-2}, which is equal to the minimum acceleration when a detonation wave is produced without the collision. The transition to detonation may be caused by the collision of a flame with a reflected shock wave if the flame acquires the energy equivalent to the difference between these two accelerations. Whether these acceleration values are applicable in all cases, regardless of various tube diameters, tube conditions, gas mixtures etc., must be further examined.

We conclude that the transition to detonation by the collision occurs in a certain region of the flame velocity or initial pressure and that the most important macroscopical factor is V_c or the mean flame acceleration between ignition and collision.

References

[1]Urtiew, A. and Oppenheim, A. K., "Experimental Observation of the Transition to Detonation," *Proceedings of the Royal Society of London*, Vol. 295A, No. 1440, 1966, pp. 13-28.

[2]Terao, K. and Sawada, R., "Stochastic Aspect of the Transition from Combustion to Detonation," *Japanese Journal of Applied Physics*, Vol. 18, No. 8, 1979, pp. 1463-1470.

[3]Jones, H., "Accelerated Flames and Detonation in Gases," *Proceedings of the Royal Society of London*, Vol. 248A, No. 1254, 1958, pp. 333-349.

[4]Markstein, G. H., "A Shock-Tube Study of Flame Front-Pressure Wave Interaction," *Sixth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, Pa., 1957, pp. 387-398.

[5]Taylor, G., "The Instability of Liquid Surface When Accelerated in a Direction Perpendicular to Their Plane I," *Proceedings of the Royal Society of London*, Vol. 201A, No. 1065, 1950, pp. 192-196.

[6]Leyer, J. C., "Inportance des Effects Dynamiques Liés au Développement de la Flamme Lors de la Combustion a Volume Constant des Mélanges Propane-Oxygene-Azote," *Revue de l'Institut Francais de Pétrole et Annales des Combustibles Liquides*, Vol. 27, No. 2, 1972, pp. 297-316.

[7]Urtiew, A. and Oppenheim, A. K., "Transverse Flame-Shock Interactions in an Explosive Gas," *Proceedings of the Royal Society of London*, Vol. 304A, No. 1487, 1968, pp. 379-385.

[8]Payman, W. P. and Titman, B. Sc., "Explosion Waves and Shock Waves, III," *Proceedings of the Royal Society of London*, Vol. 152A, No. 876, 1935, pp. 418-445.

[9]Martin, F. J. and White, D. R., "The Formation and Structure of Gaseous Detonation Waves," *Seventh Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, Pa., 1959, pp. 856-865.

[10]Inomata, T. and Suzuki, M., "The Transition to Detonation from Deflagration in Ethylene-Oxygen Systems," *Bulletin of the Chemical Society of Japan*, Vol. 50, No. 9, 1977, pp. 2247-2249.

[11]Salamandra, G. D. and Sevastyanova, I. K., "Formation of Weak Shock Waves ahead of a Flame Front and Their Intensification during Passage," *Combustion and Flame*, Vol. 7, No. 2, 1963, pp. 169-174.

[12]Evans, M. W. and Ablow, C. M., "Theories of Detonation," *Chemical Review*, Vol. 61, No. 2, 1961, pp. 129-178.

[13]Bollinger, L. E., Fong, M. C., and Edse, R., "Experimental Measurements and Theoretical Analysis of Detonation Induction Distances," *ARS Journal*, Vol. 31, No. 5, 1961, pp. 588-595.

[14]Chu, B. T., "On the Generation of Pressure Waves at a Plane Flame Front," *Fourth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, Pa., 1953, pp. 603-612.

[15]Inomata, T., Okazaki, S., Moriwaki, T., and Suzuki, M., "Shock Wave Generated by an Accelerating Flame," *Fifth Symposium on Chemical Problems Connected with the Stability of Explosives*, Sektionen för Detonic och Förbränning, Sundbyberg, Sweden, 1980, pp. 1-26.