Onset of Detonation by Forced Ignition behind an Incident Shock Wave

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1 Introduction

Deflagration to detonation transition (DDT) has been studied by many investigators and several explanations have been given to the DDT process. According to the SWACER mechanism proposed by Lee et al. [1], it is explained that if there is a spatial gradient in chemical induction time, rapid amplification of pressure pulses originating from the reaction zone eventually leads to merging with the precursor shock wave so that onset of detonation occurs. Liberman et al have shown an existence of preheated zone ahead of a propagating flame before onset of detonation [2]. The preheated zone is formed from compression of an unreacted gas in the flame acceleration process and it has been observed that a detonation bubble originates in this preheated zone. Urtiew and Oppenheim [3] have categorized the DDT process into four cases with reference to a micro-explosion and a detonation origin as follows: Detonation is initiated 1) at the flame front, 2) at the leading shock front propagating ahead of the flame, 3) at the regime between the flame and the leading shock, and 4) at the contact discontinuity generated from merging of two shock waves. Kuznetsov et al. have reported that onset of detonation is observed as the boundary layer thickness increases up to about 10 times the cell size of initial mixtures [4].

Nevertheless, knowledge on DDT is still insufficient for predicting where and when exactly onset of detonation occurs, since the following two issues make it difficult to give the prediction. One is poor reproducibility of strength of the precursor shock wave, which is responsible for variation of the position and time of a micro-explosion ahead of the accelerating flame. The other is less ability to control behavior of the flame acceleration or transition from laminar to turbulent flames.

In the present work, forced ignition of an unreacted gas behind an incident shock was conducted using a shock tube so that detonation was initiated in the fully controlled flow field. The incident shock wave was generated whose strength was as much as that of the precursor shock in the DDT process. By adjusting ignition timing the distance from the incident shock wave to the ignition position could be varied to study effects of the interaction between the propagating flame and the boundary layer on detonation initiation.

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2 Experimental

In the present work, a shock tube was used to generate an incident shock wave as shown in Fig 1. The high pressure section, which is separated from the low pressure section by an aluminum diaphragm, has an inner diameter of 50 mm. The low pressure section including the test section has a cross-section of 40 mm x 20 mm. On the upper wall of the test section, four conventional pressure transducers (PCB-H113A) were set at p1, p2, p3, and p4. One-side wall of the test section was coated by soot to observe cellular pattern.

As for the method of ignition, spark discharge and laser ablation were used. Experimental setup in each ignition method is shown in Fig.2. In Fig 2 (a), concentric planar electrodes whose gap was 1 mm was flush mounted at the middle point between p2 and p3 in Fig. 1. In this case, a capacitive spark discharge whose duration was a couple of hundreds of nanoseconds was applied to the electrodes. Spark energy of less than 10 mJ was supplied to avoid direct initiation. In laser ablation, a target made of aluminum fixed at the middle point between p2 and p3 was irradiated by Nd:YAG laser pulse whose wavelength was 532 nm. Its pulse duration was about 5-10 ns. The laser light was focused on the surface of the target through a condensing lens placed at the bottom of the test section. Laser energy was varied from 5 mJ to 195 mJ. Unlike the case of spark ignition, a blast wave was expected to be generated in the laser ablation because of relatively high energy input in shorter time.

An ethylene-oxygen mixture with equivalence ratio of 1.2 was charged into the test section as a test gas at an initial pressure of 25 kPa, 35 kPa, and 100 kPa and at a room temperature. The initial pressure P_1 and Mach number of the incident shock wave Ms were summarized in Table 1. Temperature T_2 and pressure P_2 behind the incident shock wave were calculated from P_1 and Ms. Ignition timing was controlled so that the distance from the incident shock wave to the ignition position was varied from 10 mm to 500 mm.

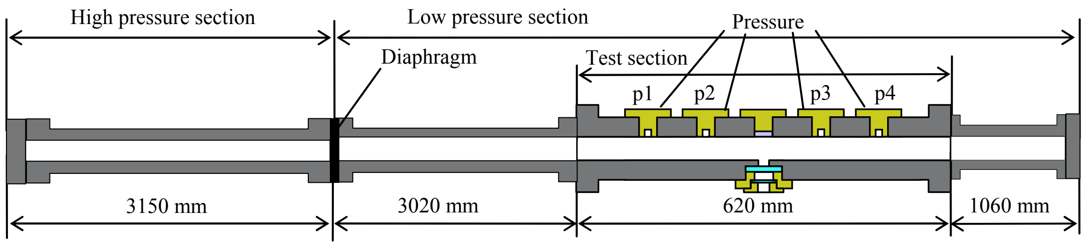
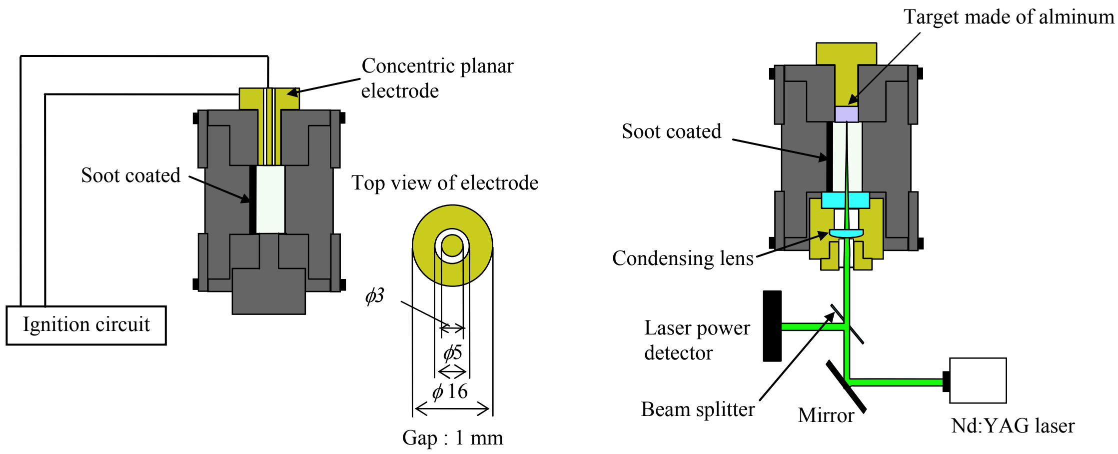


Figure 1. Schematic of shock tube



(a) Spark discharge (b) Laser ablation

Figure 2. Ignition method

Table 1. Experimental conditions.

Initial pressure, kPa	Incident Mach number	P_2, atm	T_2, K
25	2.4 ± 0.1	1.7 ± 0.2	530 ± 20
35	2.4 ± 0.1	2.4 ± 0.3	525 ± 25
100	1.7 ± 0.1	3.3 ± 0.4	400 ± 20

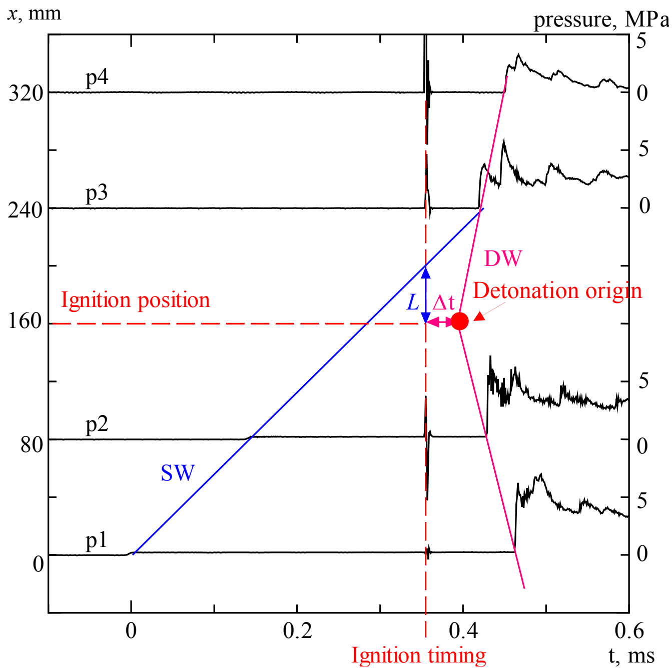
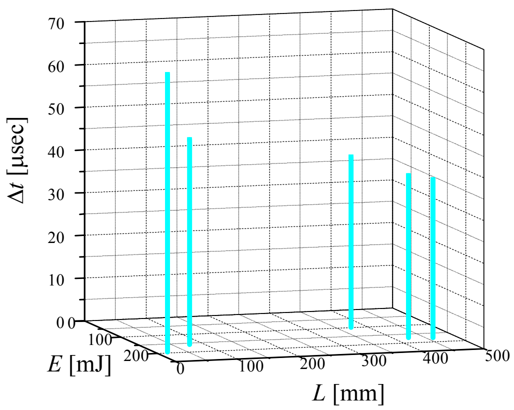


Figure 3. Pressure histories and x-t diagram. SW: incident shock. DW: detonation front. Δt: time from ignition timing to onset of detonation. L: distance from the incident shock wave to the ignition position.

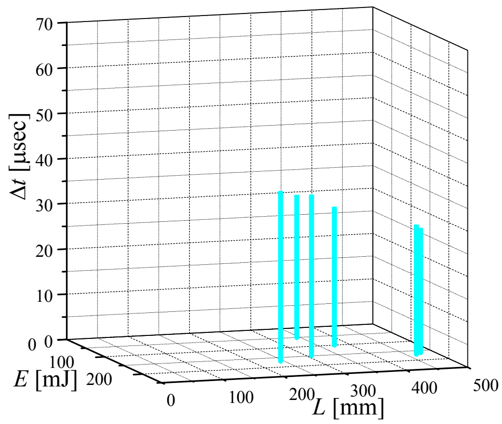
3 Results and Discussion

Typical pressure histories are shown in Fig 3. After ignition, onset of detonation occurs and detonation wave propagates in the both upstream and downstream directions. The x-t diagram of this process is also shown in Fig 3, where Δt is defined as the time from the ignition timing to generation of detonation origin and L denotes the distance from the incident shock wave to the ignition position. The position and timing of detonation origin was estimated from the detonation speed propagating upstream and downstream. Figure 4 shows effects of the spark energy E and the distance L on Δt estimated as shown in Fig. 3 for the initial pressure of 25 kPa, 35 kPa, and 100 kPa. It is found that there is a tendency that ignition whose position is located further from the incident shock wave causes prompt initiation of detonation. This tendency is independent of the initial pressure, ignition energy, and the ignition method as shown in Fig 4. Since the flow properties behind the incident shock wave do not significantly change for the cases of larger value of L, it is considered that development of the boundary layer at the vicinity of the wall affects the process of the detonation initiation.

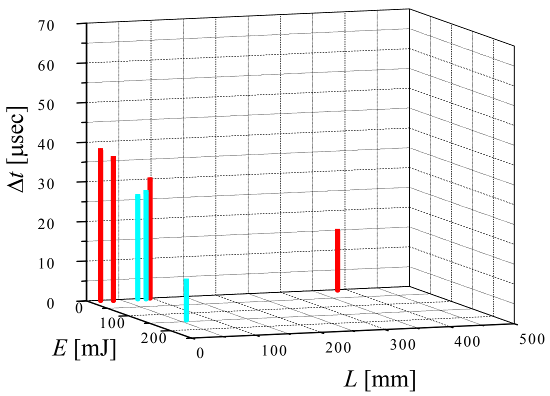
The case of spark ignition, in which effects of a blast wave on the flow filed can be excluded, is suitable for consideration of onset of detonation near the boundary layer. Figure 5 (a) and (b) show soot records for the cases of the spark ignition with E of 4.1 mJ, 5.7 mJ and L of 19 mm, 385 mm, respectively. In the both cases an arch-like line, inside which a cloud-like pattern is drawn, is observed on the soot record, although an area enclosed by the arch-like line is different. Just after ignition by spark discharge, a flame propagates with a subsonic speed relatively to the flow and thus it is deduced that the flame does not reach the bottom wall of the test section within Δt in all the tests which is summarized in Table 2. The arch-like line, therefore, demonstrates the flame front at which detonation wave passes in the unreacted gas. This is consistent with the fact that the area enclosed by the arch-like line, S, increases monotonically with Δt as shown in Table 2, where the area is estimated from the maximum horizontal width w and the height of the arch-like line h under the assumption that the area is approximated as a triangle.



(a)A relationship of ignition energy, the distance from the incident shock wave to the ignition position, and the time from the ignition timing to the detonation origin. Laser ablation at initial pressure 25 kPa; shock Mach number Ms = 2.4 ± 0.1, T_2 = 530 ± 20 K, P_2 = 1.7 ± 0.2 atm.



(b)A relationship of ignition energy, the distance from the incident shock wave to the ignition position, and the time from the ignition timing to the detonation origin. Laser ablation at initial pressure 35 kPa; shock Mach number Ms = 2.4 ± 0.1, T_2 = 525 ± 25 K, P_2 = 2.4 ± 0.3 atm.



(c)Comparison of ignition methods (spark discharge and laser ablation). Initial pressure 100 kPa; shock Mach number Ms = 1.7 ± 0.1, T_2 = 400 ± 20 K, P_2 = 3.3 ± 0.4 atm.

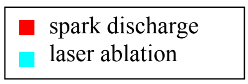


Figure 4. Effects of ignition energy, the distance from the incident shock wave to the ignition position and the time until onset of detonation.

From the above consideration it is suggested that the detonation initiation is governed by the propagation manner of the flame near the wall surface, namely the boundary layer. In the case that spark discharge is made immediately after passage of the incident shock wave, the flame propagates in the main flow drifting downstream. As for longer distance from the incident shock wave to the ignition position, the flame initially develops within the turbulent boundary layer together with transition from laminar to turbulent flame. This provides a large heat release rate, which finally leads to generation of a shock wave or detonation initiation. The boundary layer displacement thickness δ calculated by the Fay's method [6] is shown in Table 2. Further quantitative discussion will be needed to specify the condition of detonation initiation.

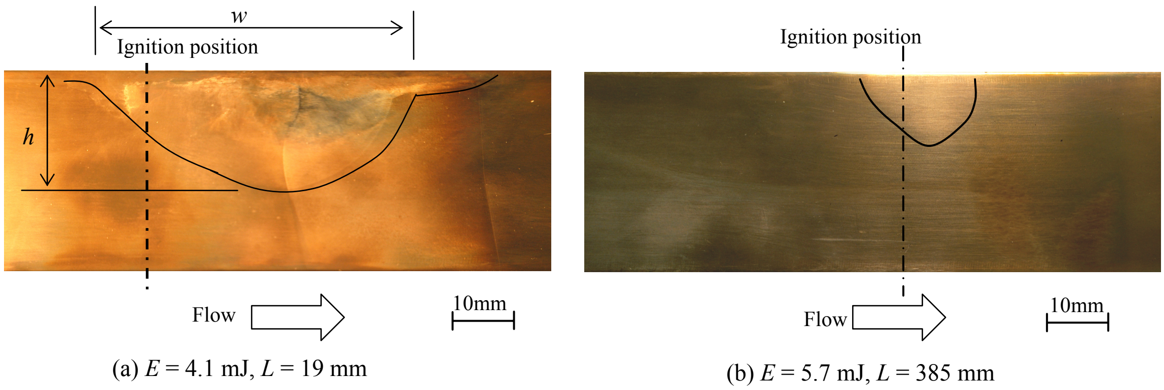


Figure 5. Soot record for spark discharge at initial pressure of 100 kPa

Table 2. All results of spark ignition at 100 kPa, Ms = 1.7 ± 0.1, T_1 = 400 ± 20 K, P_2 = 3.3 ± 0.4 atm. S: The area of enclosed by the arch-like line approximated as a triangle.

Test number	E, mJ	L, mm	Δt, μs	w, mm	h, mm	S, mm^2	δ, mm
1)	4.1	19	38	53	14	371	0.3
2)	3.4	36	36	50	13.5	337	0.5
3)	8.2	96	30	55	-	-	1.1
4)	5.7	385	15	27	12	162	3.3

4 Summary

Onset of detonation by forced ignition behind an incident shock wave in ethylene-oxygen mixture has been experimentally studied. Spark discharge and laser ablation were used for ignition source behind an incident shock wave which was treated as the precursor shock wave formed ahead of accelerating flame in the DDT process. The experimental results show that there is a tendency that the time from the ignition timing to detonation initiation decreases with increase in the distance from the incident shock wave to the ignition position.

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