Deflagration to Detonation Transition behind an Incident Shock Wave by Forced Ignition

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1 Introduction

Deflagration to detonation transition (DDT) occurs by flame acceleration in a smooth tube filled with a combustible mixture. Many researchers have tried to analyze the DDT process [1-3]. Urtiew and Oppenheim [1] showed four modes of DDT with reference to the origin of detonation as follows: Detonation is initiated 1) at the flame front, 2) at the precursor shock front overtaken by a tip of propagating flame along boundary layer, 3) at the region between the flame and the precursor shock, and 4) at the contact discontinuity generated from merging of two shock waves. Generally, several compression waves generated in front of the accelerating flame compress the unburned gas, so that temperature and pressure of the gas rise gradually. Meyer et al. [2] estimated temperature and pressure of the unburned gas behind compression waves during the DDT process from their strength. Nevertheless, the result shows that the estimated temperature is not high enough for self-ignition of the mixture resulting in detonation initiation from only a single local explosion. Kuznetsov et al. [3] focused on the fact that the local explosion mostly occurs near the tube wall. They have shown that detonation is initiated when the scale of the turbulent pulsations, δ, at the flame position reaches about 10 times the cell size of the initial mixture. However, as this result was reported for stoichiometric hydrogen oxygen, a prediction of position or timing with other mixture has not been carried out.

At the present it is still a hard task to predict position and timing of onset of detonation or a local explosion leading to DDT. This is partly because accurate measurement of mixture conditions required for local explosions is difficult. Usually DDT distance and time varies in each test, which is due to less repeatability of turbulent flame propagation and formation of the precursor shock wave.

In our previous work [4], a mixture behind an incident shock wave was ignited using a shock tube to improve repeatability of DDT phenomena, in particular with a focus on formation of the precursor shock wave. Detonation initiation was succeeded by forced ignition with laser ablation and spark discharge with good repeatability in the position and timing of onset of detonation. This makes it easier to visualize the whole process of detonation initiation than traditional experimental methods using accelerating flames in tubes. In the present work, a test gas has been ignited by spark discharge near the tube wall as in the present work. High-speed schlieren photographs of the process of

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detonation initiation have been taken to estimate state of an unburned gas just before the onset of detonation.

2 Experimental

A shock tube used in the present work is a standard one, which is composed of a 3020 mm long high pressure and a 4070 mm long low pressure section. The former is a stainless steel tube 50 mm in inner diameter, while the latter including a test section has a rectangular cross section of 40 mm × 20 mm. Details of the shock tube configuration are described in the previous paper [4]. Four conventional pressure transducers p1-p4 and a concentric spark electrode, which is used not to disturb the flow field, are mounted on the upper wall of the test section, as shown in Figure 1. A pair of windows of Plexiglas is installed on the side wall for visualization tests. Schlieren photographs of the whole process of detonation initiation are taken with a high speed camera (nac, ULTRA Cam HS-106E) and a conventional xenon flash light source

The test gas is an ethylene-oxygen mixture with equivalence ratio of 1.2 and is charged in the low pressure section at an initial pressure of 25 kPa and a room temperature.

In operation, an incident shock wave is generated by rupture of a diaphragm separating the high and low pressure section. Mach number of the incident shock wave, M_s is in the range of 1.9 to 2.6, which corresponds to strength of the precursor shock wave in usual DDT events. After the incident shock wave passes the spark electrode, the shock-compressed test gas is ignited by spark discharge at a desired time. As a capacitance spark is used in the present work, spark duration is a couple of hundreds nanoseconds. Spark current and voltage are recorded to calculate spark energy. To avoid direct initiation, spark energy supplied to the test gas is limited to less than 10 mJ. Triggering the spark discharge is controlled so that the distance between the spark electrode and the incident shock wave at the ignition timing varies from 6 mm to 610 mm.

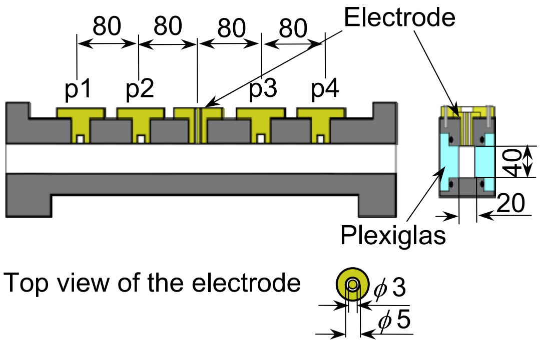

Figure 1. Schematic of test section.

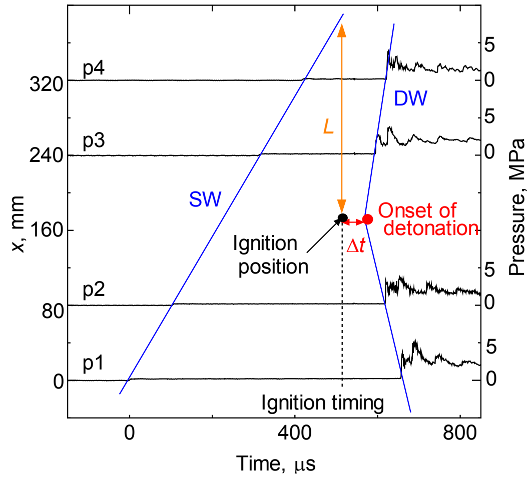

Figure 2. Typical pressure histories and *x-t* diagram. SW: Incident shock wave. DW: Detonation front. Δt: Period of time from the ignition timing to onset of detonation. L: distance from the incident shock wave to the ignition position.

3 Results and Discussion

3.1 Period of time for detonation initiation

Figure 2 shows typical pressure histories and the *x-t* diagram of wave motions. Time of zero corresponds to the time when the incident shock wave arrives at the pressure sensor p1. Then 450 µs later the shock-compressed gas is ignited and at that time the incident shock moves 370 mm away from the ignition position. In Figure 2, L denotes the distance between the ignition position and the location of the incident shock wave at the ignition timing. Although the present spark electrode has a concentric shape, ignition position is assumed to be its center, namely x = 160 mm. After igniting the test gas, rapid pressure risings are detected at p1-p4, which are due to arrival of the detonation front propagating in the upstream and downstream directions. Extrapolation of these wave motions in the *x-t* diagram can specify time and location of onset of detonation as shown in Figure 2. As a result, Δt, which is defined as period of time from the ignition timing to the onset of detonation, is estimated to be 50 μs.

As the test gas is ignited on the wall surface of the test section, the flame kernel generated by spark discharge develops at first in the boundary layer. In order to clarify effects of boundary layer on the process of detonation initiation, the distance from the incident shock to the ignition position, L was varied. This leads to change boundary layer thickness and a boundary layer Reynolds number, Re_0, of the ignition position and at the ignition timing. Re_0 behind an incident shock wave is defined by the following equation [5]

$$\mathrm{Re}_0 = (V_s - u_2)\frac{\left(\dfrac{\rho_2}{\rho_1}-1\right)^2}{\dfrac{\rho_2}{\rho_1}\nu_2}L, \tag{1}$$

where, V_s, u, ρ, ν denote velocity of the incident shock wave, density, kinetic velocity and subscripts 1 and 2 represent an initial and a shock-compressed state, respectively. Figure 3 shows the period of time for detonation initiation, Δt for various the boundary layer Reynolds numbers. As shown in the previous work [4], the same tendency is confirmed that increase in Re_0 causes prompt detonation initiation. Furthermore, it is found that this tendency is almost independent of the incident shock Mach number, M_s. From these results, Δt can be estimated to be proportional to $Re_0^{-0.3}$.

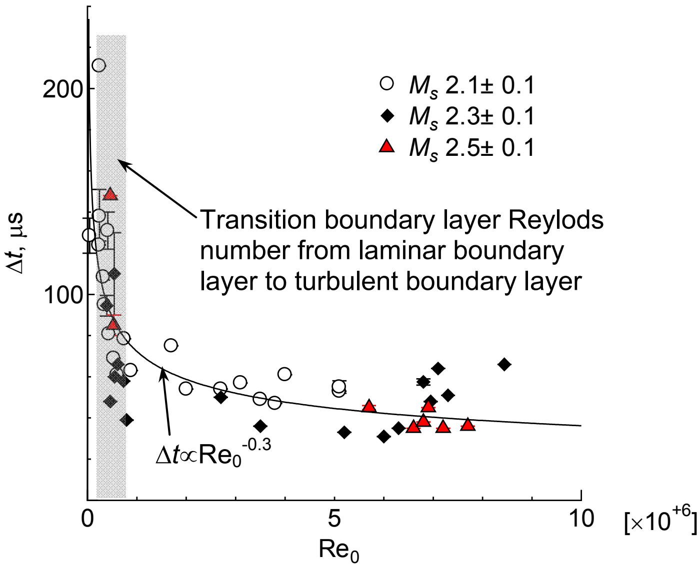

Figure 3. Variation of period of time for detonation initiation with boundary layer Reynolds number of the ignition position at the ignition timing. Gray region denotes transition Reynolds number from laminar to turbulent.

As is well known, transition from a laminar to a turbulent boundary layer occurs behind travelling shock waves. From shock tube experiments [6], it is reported that a transition boundary layer Reynolds number, Re_t, is in the following ranges: $2.0 \times 10^5 \leq Re_t \leq 4.0 \times 10^5$. As shown in Figure 3, the value of Δt drastically decreases with increase in Re_0 in the case of Re_0 of less than 1.0×10^6, while Δt is within 48 ± 21 μs for Re_0 of 1.0×10^6. This result suggests that flame kernel development and further propagation is promoted when the spark ignition is made in the turbulent boundary layer. It is found in Figure 3 that variation in Δt has less scatter for a sufficiently thick boundary layer, in particular, $Re_0 \geq 5.0 \times 10^6$ and that Δt is 45 ± 10 μs in the case excluding M_s of 2.3 ± 0.1. This indicates that good reproducibility can be obtained with respect to detonation initiation in the present experiment. As for M_s of 2.3 ± 0.1, Δt gradually increases with Re_0 for $Re_0 \geq 7.0 \times 10^6$. This tendency is not observed for the other incident Mach numbers and further studies are needed.

3.2 Schlieren photographs and analysis of wave motion

A part of sequential schlieren images of the detonation initiation process are shown in Figure 4. These images were taken under the condition of $Re_0 = 6.9 \times 10^6$ and $\delta_0 = 5.2$ mm. Here δ_0 is boundary layer

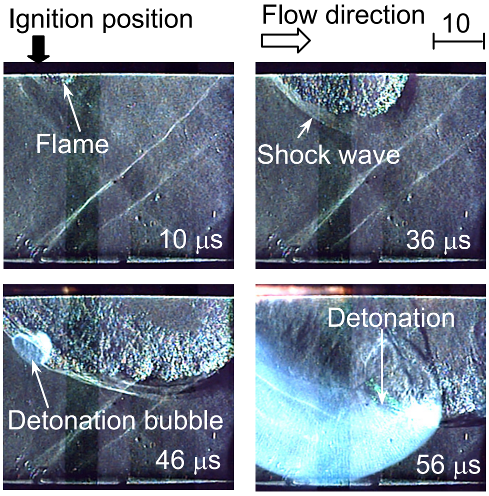

Figure 4. Sequential schlieren photographs of propagating flame and an onset of detonation. Time from the ignition is shown at right bottom of each image. $Re_0 = 6.9 \times 10^6$, $\delta_0 = 5.2$ mm.

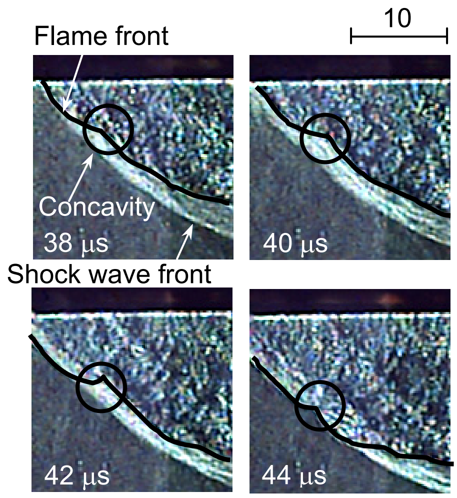

Figure 5. Enlarged images of flame front near the location where the detonation bubble appears.

thickness at the ignition position and at the ignition timing and is estimated by the following equation [7]

$$\delta_0 = 0.22 x^{0.8} \left(\frac{\mu_1}{\rho_1 V_s} \right)^{0.2}, \tag{2}$$

where μ_1 denotes viscosity of a mixture of an initial state. Frame rate of the high speed camera was set at 5×10^5 fps, resulting in a frame interval of 2 μs and time of zero corresponds to the spark discharge timing. In Figure 4, at 36 μs a shock wave is generated ahead of the flame. A separation distance between the flame and the shock wave front on the left side is shorter than on the right side, which is due to slower relative velocity of the shock wave travelling upstream. At 46 μs a detonation bubble appears in the vicinity of the flame front at the upstream side, where the flame front makes close approach to the shock wave front. Then at 56 μs a semi-spherical detonation wave can be observed with strong emission.

Figure 5 shows enlarged schlieren images near the location where the detonation bubble is generated in Figure 4. It is found that the origin of the detonation bubble is very close to a concavity of the flame front shown in the image of 38 μs. Although the flame front makes the closest approach to the shock wave front at 44 μs, the detonation bubble does not appear until 46 μs. Since the size of detonation bubble is about 8 mm in diameter at 46 μs, it is deduced that detonation is initiated between 44 μs and 46 μs. Thus Δt is estimated to be 45 μs. This estimation is in good agreement with $\Delta t = 41$ μs obtained from the corresponding x-t diagram.

Using the high speed schlieren images, motion of the shock wave was analyzed to obtain a state of the unburned gas at the origin of detonation bubble. Figure 6 illustrates trajectories of points (A)-(F) located on front of the shock wave. Each curve is the wave front of the shock wave drawn from the schlieren images. Because flow velocity u_2 and location of the wave fronts F_1, F_2 in two sequential frames are known, a trajectory of the point on the wave front can be determined by calculating wave velocity V_p which is normal to the wave front. A trajectory (C) is found to reach the location where the detonation bubble appears. This analysis gives wave velocity V_p at each point on the wave front. Figure 7 shows Mach number histories of V_p at the trajectories (A)-(F). For the trajectories (A) and (B), the wave Mach numbers gradually increase at 28 μs ~ 34 μs and then remains almost constant of 2.0. At 40 μs they rapidly accelerate to 2.6. On the trajectory (D) the wave Mach number is nearly constant of unity from 10 μs to 18 μs. However, it accelerates to 1.6 at 20 μs. After that, the Mach number is

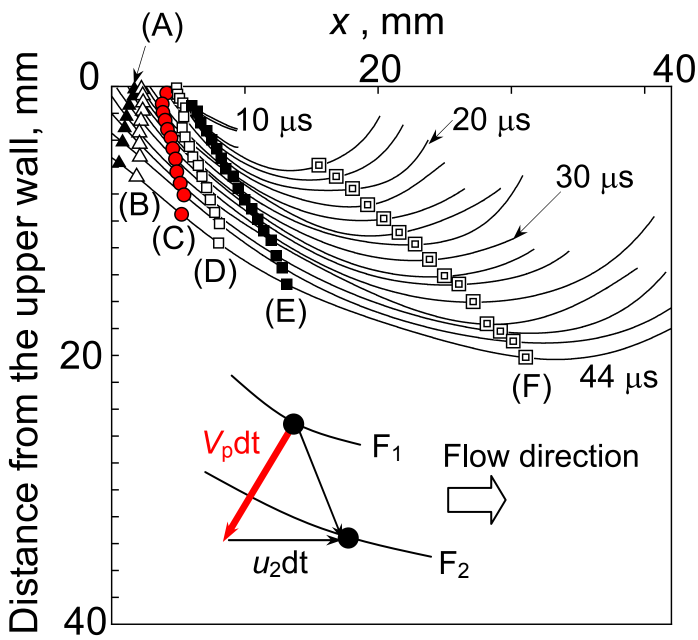

Figure 6. Compression wave motions and point trajectories (A)-(F) on the waves from 10 μs to 44 μs, just before detonation initiation. F_1, F_2: shock wave front, V_p: wave velocity, u_2: flow velocity behind the incident shock wave.

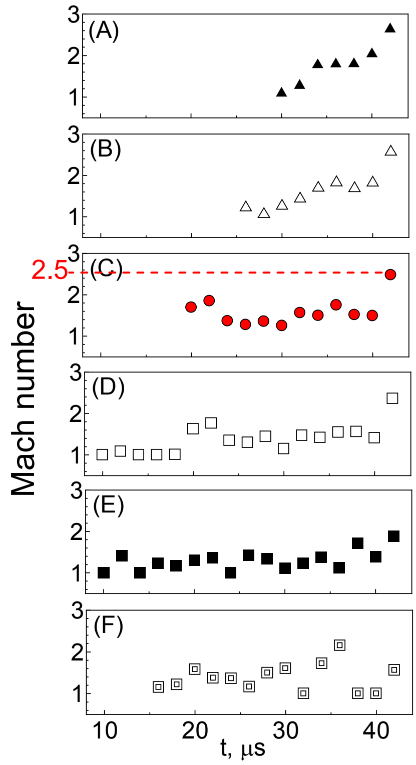

Figure 7. Mach number histories of velocity at each point on the shock wave front.

almost constant until 40 μs and rapidly increases. The wave Mach number on the trajectory (C) has the same trend as on the trajectory (D). Just before onset of detonation the wave Mach number reaches 2.5. Although there is gradual acceleration on the trajectory (E) after 36 μs and the wave Mach number increases to 2.2 on the trajectory (F) at 36 μs, a detonation bubble is not generated for the both points. Only on the trajectory (C), a rapid increase of Mach number from 1.5 to 2.5 in 2 μs interval is observed just before onset of detonation. It must be noted that effects of the concavity on wave motion is not considered in the present wave analysis, so that the wave front is treated as a smooth curve. Existence of the concavity might be related to local strong compression causing detonation initiation.

Based on the results of the wave analysis it is possible to estimate temperature of the unburned gas behind the shock wave. At first the test gas charged in the test section is compressed by the incident shock wave of Mach number of 2.4, leading to increase in temperature up to 530 K. Then, the test gas is compressed by the shock wave generated from flame development, and its temperature rises to over 870 K just before the onset of detonation. However, this temperature is lower than 1100 K, which is self-ignition limit of most hydrocarbon fuels [8]. Consequently, additional explanation to describe the onset of detonation is needed. At least there should be other local strong compression mechanism to increase temperature of the unburned gas. In Figure 7, the wave Mach number on the trajectories (A) and (B) are higher than that on the trajectory (C) at 44 μs. This means that temperature on (A) and (B) is higher than (C), which is contradictory to the fact that a detonation bubble is generated on the trajectory (C). In combination with effects of the concavity further researches are needed to clarify state of the unburned mixture just before onset of detonation.

4 Summary

To improve repeatability of phenomena of detonation initiation, an ethylene-oxygen mixture compressed by an incident shock wave was ignited by spark discharge. The distance between the incident shock wave and ignition position has been varied by controlling ignition timing. High-speed schlieren photographs of the process of detonation initiation were taken to estimate state of an unburned gas just before onset of detonation.

Experimental results show that time of onset of detonation calculated from extrapolation of wave motions in the *x*-*t* diagram is in good agreement with that shown in the schlieren images. The period of time for detonation initiation, Δt, is proportional to $Re_0^{-0.3}$ independently of Mach number of the incident shock wave. In particular Δt is 45 ± 10 μs for $Re_0 \geq 5.0 \times 10^6$. This result demonstrates that good reproducibility can be obtained with respect to detonation initiation by the present experimental method.

Temperature of the unburned gas just before onset of detonation was evaluated on the bases of analysis of motion of the shock wave generated from flame development. From this analysis, onset of detonation occurs in the present work from the following scenario:

(1) The test gas is compressed by the incident shock wave with Mach number of 2.4.
(2) The shock-compressed test gas is ignited on the wall surface by spark discharge.
(3) A shock wave of Mach number of over 2.5 is generated from flame development.
(4) The unburned gas is locally compressed at the accelerating flame front with sufficient proximity between the flame and shock front.

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