Effects of Boundary Layer on Flame Propagation Generated by Forced Ignition behind an Incident Shock Wave in DDT Process

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1 Introduction

Detonation initiation from deflagration to detonation transition (DDT) has been intensively studied [1–5]. Although DDT can be caused in various situations, a smooth wall tube filled by a combustible mixture is well used for studies of spontaneous ignition by flame acceleration. The mixture ignited at a closed end of the tube induces a flame followed by detonation initiation depending on initial states. Urtiew and Oppenheim have been known for taking clear photos of sequential flame propagation and detonation transition [1]. They have shown that detonation initiations have often occurred in the vicinity of the inner wall of the flow channel. Compression waves ahead of accelerating flame merge and strengthen as a precursor shock wave. Therefore, region near the inner wall of the channel is highly complex due to interaction between flame front, shock wave and boundary layer. Kuznetsov et al. have shown that the maximum scale of turbulent pulsations (boundary layer thickness) up to about ten times of the cell size of the mixture can trigger detonation [2]. However, this result is limited to a stoichiometric hydrogen-oxygen mixture. General investigation for predicting DDT position and timing is still difficult, since propagating flame, which is hardly controllable, and complex gasdynamical interactions make DDT less reproducible.

In the authors' previous studies to improve controllability and repeatability of DDT phenomenon, a mixture behind an incident shock wave was ignited by spark discharge with energy of less than 10 mJ [3, 4]. A leading shock wave in the usual DDT process was replaced with the incident shock wave, so that its strength could be easily controlled. Propagating flame was replaced with a flame generated by spark discharge after passage of the incident shock wave. As a result, detonation was initiated with high repeatability both in the position and the timing. Furthermore, it was found that flame propagation was affected by the boundary layer near the wall. For turbulent boundary layers, flame development leading to DDT was promoted, while for laminar boundary layers detonation initiation required more time to initiate. Hence, in the present work the mixture is forcibly ignited apart from the wall surface in order to study effects of boundary layer on the flame propagation.

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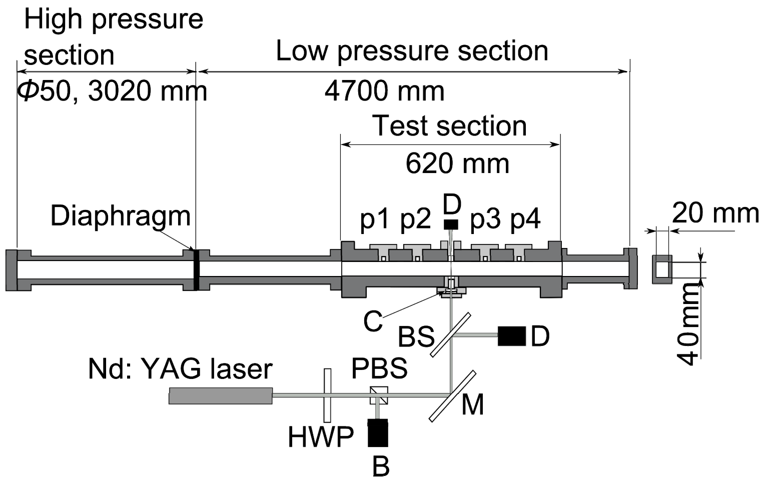

Figure 1. Schematic figure of shock tube and laser ignition system. HWP: half wave plate, B: beam stopper, PBS: polarizing beam splitter, M: mirror, BS: beam splitter, C: condensing lens, D: laser power detector.

2 Experimental

In the present work, a shock tube shown in Fig. 1 was used to generate an incident shock wave. The tube is composed of a 3020 mm high pressure section and a 4700 mm low pressure section including a 620 mm test section. The tube with 50 mm inner diameter was used as the high pressure section, which was separated from the low pressure section by an aluminum diaphragm. The low pressure section including the test section has a rectangular cross-section of 40 mm × 20 mm. For side walls of the test section a set of Plexiglas windows are used for visualization by high speed cameras (Ultra 8 and ULTRA Cam HS-106E, nac image technology). On the upper wall of the test section, four conventional pressure transducers are used (denoted as p1, p2, p3, and p4) in a symmetrical manner so that distance between p1 and p2 is the same as the distance between p3 and p4, i.e. 80 mm. The distance between p2 and p3 is 160 mm.

Forced ignition is induced by laser breakdown with Nd:YAG laser (wavelength: 532 nm, pulse width: 8 ns). The laser light enters to the test section through an optical system illustrated in Fig. 1. The laser light passes through a condensing lens (f = 100 mm) mounted below the test section, so that the laser focal point, i.e. laser ignition position can be varied in the vertical direction. The vertical distance from the upper wall y_0 is 2.5 ± 0.5 mm, 5.5 ± 1.0 mm and 11 ± 0.5 mm. Amount of laser energy absorbed by the mixture is estimated using laser power detectors. Energy used for igniting the mixture was found to be less than 10 mJ, which was small enough to avoid direct initiation of detonation. As a test gas, an ethylene-oxygen mixture with an equivalence ratio of 1.2 was filled in the low pressure section at a room temperature and at an initial pressure of 25 kPa. Mach number of the incident shock wave M_s was 2.1 ± 0.1 and 2.3 ± 0.1. The gas state behind the incident shock wave is obtained from the initial state, 480 ± 20 K and 130 ± 20 kPa for M_s of 2.1 and 520 ± 20 K and 160 ± 20 kPa for M_s of 2.3.

Shortly after the incident shock wave passed halfway between p2 and p3, a laser light was irradiated and focused in the flow channel. The distance from the incident shock wave to the ignition position x was varied from 10 mm to 600 mm by controlling the ignition timing.

3 Results and discussion

Detonation initiation timing is estimated from the timing of rapid pressure rising in pressure history. Time required for detonation initiation is denoted as Δt. Boundary layer thickness δ_0 behind an incident shock wave at the ignition timing and at the ignition position is calculated from an empirical equation [6];

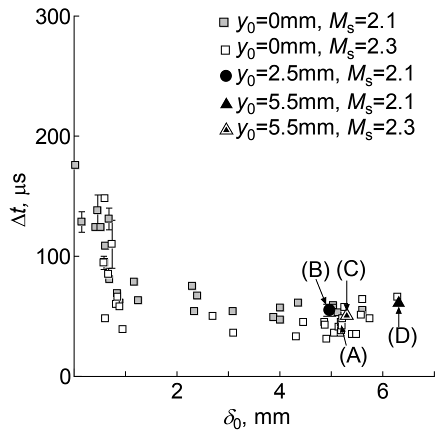

Figure 2. Required time for detonation initiation versus the boundary layer thickness in the case of forced ignition inside the boundary layer.

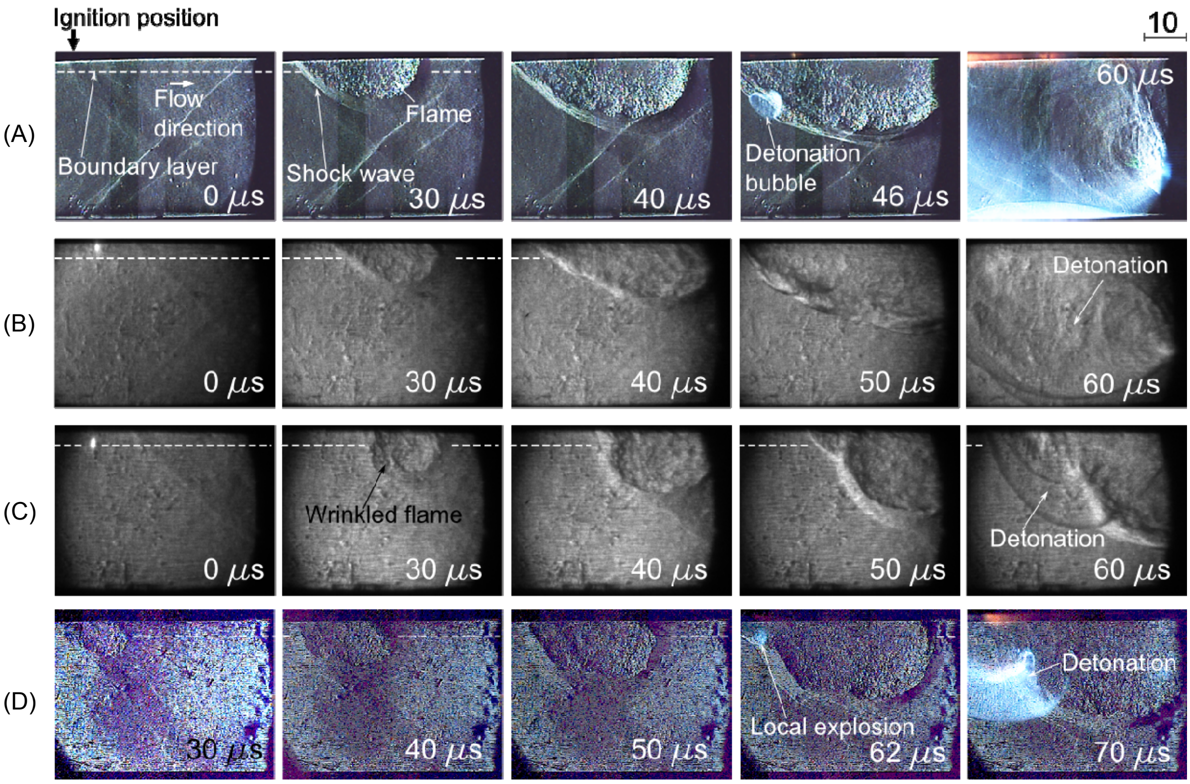

Figure 3. Propagating flame and detonation initiation in the case of forced ignition inside the boundary layer. (A) - (D) correspond to them in Fig. 2. (A) $y_0 = 0$ mm, $M_s = 2.4$, $\delta_0 = 5.2$ mm, (B) $y_0 = 2.5$ mm, $M_s = 2.2$, $\delta_0 = 5.0$ mm, (C) $y_0 = 5.5$ mm, $M_s = 2.2$, $\delta_0 = 5.0$ mm, (D) $y_0 = 5.5$ mm, $M_s = 2.0$, $\delta_0 = 6.3$mm.

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

where μ, ρ_1 and V_s denote the viscosity at the outer edge of the boundary layer, the density of the initial state and the shock velocity, respectively. Figure 2 shows required time for detonation initiation versus the initial boundary layer thickness in the case of forced ignition inside the boundary layer. For reference, results of forced ignition at the wall surface, namely y_0 of 0 mm, are plotted. There is no

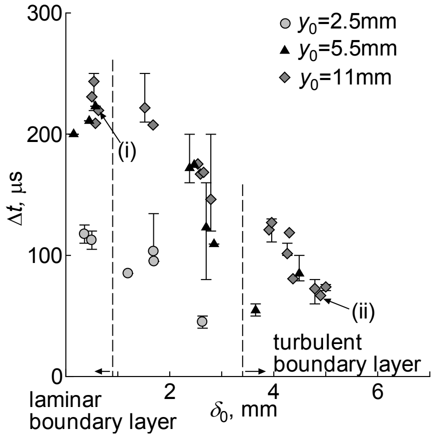

Figure 4. Required time for detonation initiation versus the boundary layer thickness in the case of forced ignition outside the boundary layer for M_s of 2.1.

significant difference in the time for detonation initiation between y_0 of 0 mm, 2.5 mm and 5.5 mm as shown in Fig. 2. For ignition inside the turbulent boundary layer, required time for detonation initiation was 56 ± 6 μs for y_0 of 2.5 mm and 5.5 mm, which is in good agreement with the result for y_0 of 0 mm. In Fig. 3 Schlieren images of (A) to (D), which correspond to (A) to (D) in Fig. 2, are demonstrated. There is also no significant difference in the process of detonation initiation in spite of the different ignition positions. In the case of forced ignition on the wall, spark discharge with short duration of less than 1 μs was used. The electrode was concentric and flush mounted at the flow channel to avoid disturbing the flow. Therefore, DDT induced in the present work is not affected by the type of forced ignition. After the propagating flame reaches near the upper wall, the flame is stretched in the upstream direction by the existence of velocity gradient. This flame stretch triggers detonation initiation near the flame front.

In the case of forced ignition outside the boundary layer for M_s of 2.1, required time for detonation initiation is shown in Fig.4. Here, a dashed line represents a line of demarcation between laminar and turbulent boundary layer. The time for detonation initiation monotonically decreases with increase in the initial boundary layer thickness independent of the ignition position. DDT with high repeatability could be caused by forced ignition at away from the wall. Schlieren images of (i) and (ii) in Fig. 4 are demonstrated in Fig. 5. In Fig. 5 (i), the boundary layer cannot be seen unlike in Fig. 5(ii). Propagating flame remains laminar and spherical before contacting to boundary layer or wall as shown in Fig. 5 (i). Figure 6 shows history of flame kernel size in the vertical direction, l_v and the horizontal direction, l_h during propagation in the main flow without contacting to any boundary layer or wall. It is found that l_v and l_h increase linearly with increase in time. Up to 30 μs from the laser induced timing, flame

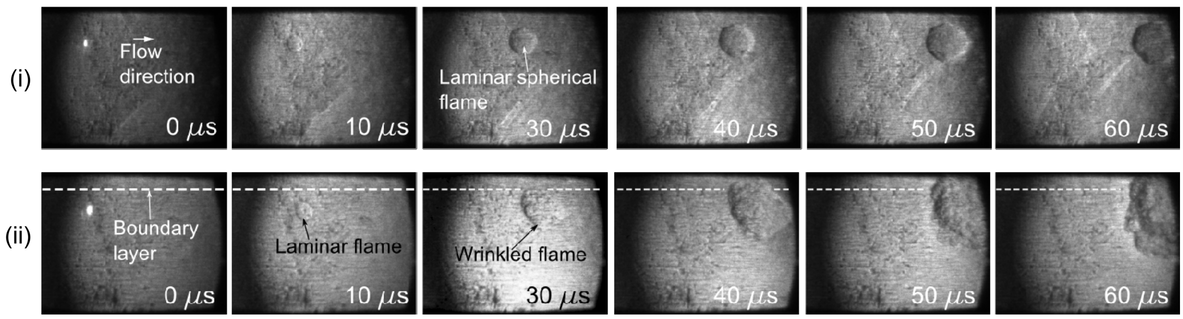

Figure 5. Propagating flame in the case of forced ignition outside the boundary layer. (i) and (ii) correspond to them in Fig. 4. (i) y_0 = 11 mm, M_s = 2.2, δ_0 = 0.6 mm (The boundary layer cannot be seen in the images.), (ii) y_0 = 11 mm, M_s = 2.1, δ_0 = 4.9 mm.

kernel for M_s of 2.3 is smaller than M_s of 2.1 due to its higher heat loss to the surrounding gas. However, since the temperature and pressure of the surrounding gas are higher, larger flame spreading rate for M_s of 2.3 was obtained compared to that for M_s of 2.1. Assuming the flame width in the direction of normal to a paper plane is equal to l_v, the flame reaches at the side boundary layers of 5 mm at 24 μs for the case of y_0 of 11 mm. Moreover, the timing of flame-upper boundary layer interaction is estimated to be at 32 μs. These estimations are in good agreement with the visualization results in Fig. 5 (ii). At 30 μs, the flame surface is wrinkled mainly disturbed by turbulence near outer edge of the turbulent boundary layer in vicinity of the side walls. Simultaneously, the flame reaches the upper boundary layer. The flame is transformed at 40 μs due to the velocity gradient in the upper boundary layer. At 50 μs, the flame surface is more wrinkled. The flame kernel is estimated to reach the side walls at 55 μs. Then, the flame is more affected and stretched by strong velocity gradient near the walls, resulting in transformation and acceleration followed by detonation transition.

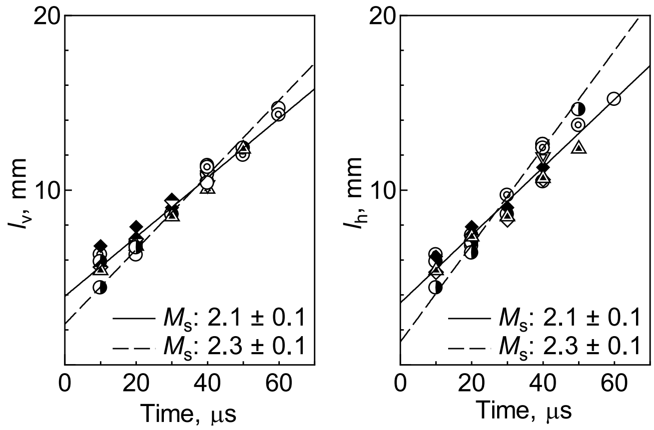

Figure 6. History of flame kernel size for y_0 of 11 mm before contacting to neither the boundary layer nor the walls. l_v: vertical length of the flame kernel. l_h: horizontal length of the flame kernel.

4 Summary

In order to investigate the effects of boundary layer on the flame propagation which causes detonation initiation, an ethylene-oxygen mixture was forcibly ignited behind an incident shock wave using laser breakdown. The ignition timing was controlled and the ignition position from the upper wall was varied as 2.5 mm, 5.5 mm and 11 mm, so that the mixture was ignited inside or outside the boundary layer. The process of flame propagation was visualized by Schlieren imaging. It was found that DDT with high repeatability could be caused by forced ignition independent of the forced ignition position.

For ignition inside the turbulent boundary layer, the flame front was stretched near the wall, resulting in DDT. The required time and the process for detonation initiation were not affected by the Mach number of the incident shock and the ignition position. Therefore, DDT induced in the present work was independent of the type of forced ignition. On the other hand, in the case of the forced ignition outside the boundary layer, the propagating flame keeps laminar and spherical before contacting to boundary layer or wall. The height and width of flame kernel increased linearly with increase in time. After interacting with turbulent boundary layer, the flame was wrinkled by turbulent boundary layer, resulting in prompt detonation transition.

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