Experimental Study on the Combination of Laser Ignition and Shock Focusing Method for Detonation Initiation

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1 Background

Detonation is a supersonic combustion phenomenon propagating at 2 to 3 km/s. As it conducts chemical reactions in highly compressed propellants, detonation is anticipated to be applied as a next-generation propulsion system. Conventionally, there are two methods to initiate detonation. The first one is Deflagration-to-Detonation Transition (DDT) which requires a few milli-joules to initiate detonation [1] but takes a few hundred millimeters so that a flame kernel turns into a detonation wave [2]. The other one is Direct Ignition (DI) which is capable of initiating detonations in a few millimeters [3] though it requires a few thousand millijoules for successful initiation [4]. Considering the pros and cons of DDT and DI, a new method with the merits of both methods is now under investigation.

This study proposes combining laser ignition and shock focusing for detonation initiation. Laser ignition is such a way that uses a high-power laser beam to start combustion [5]. Due to its high energy density, a spherical shock wave will be generated after laser irradiation [6]. Though the shock wave decays soon, by reflecting and converging, a local explosion is expected to occur and trigger detonation. This method is so unique from the perspective of engineering that laser ignition offers obstacleless room for shock focusing, unlike conventional spark-plug ignition. Furthermore, this method is also interesting academically because it utilizes a spherical shock wave formed by laser ignition while previous studies used planar shock waves as their experiments were conducted in a shock tube [7].

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Since little has been clarified about the feasibility of this method to initiate detonation, this study conducted laser ignition experiments using a flow-visualizable combustor with three different cavities and verified if detonation is achievable by shock focusing.

2 Experimental Setup and Conditions

Figure 1 shows the cross-section of the combustor used in the experiment. The combustor is 50x50x60 mm (60 mm in the longitudinal direction) and has a 23 mm square hollow in which a 3D-printed cartridge with a cavity is inserted. This cartridge has a 3 mm thickness and is enclosed by PMMA windows and TEMPAX Float glasses which are parallel to the paper. There is a conical hole at the right end of the combustor for the incoming laser beam and a through hole at the left end to check if the laser beam vertically enters the combustor. The variety of the cavity's shape is described in Figure 2. ELP is the one that an ellipse (major radius: 4 mm; minor radius: 2 mm) and a rectangular (2 mm height) are connected. The other cavities, the RCT series, are rectangular cavities with 2 mm or 4 mm in height. The coordinate system in the figure defines the central line for Mach number calculations. The origin was taken at the left end of the cavity and the *x* axis was defined in the longitudinal direction which is negative to the direction of the incoming laser.

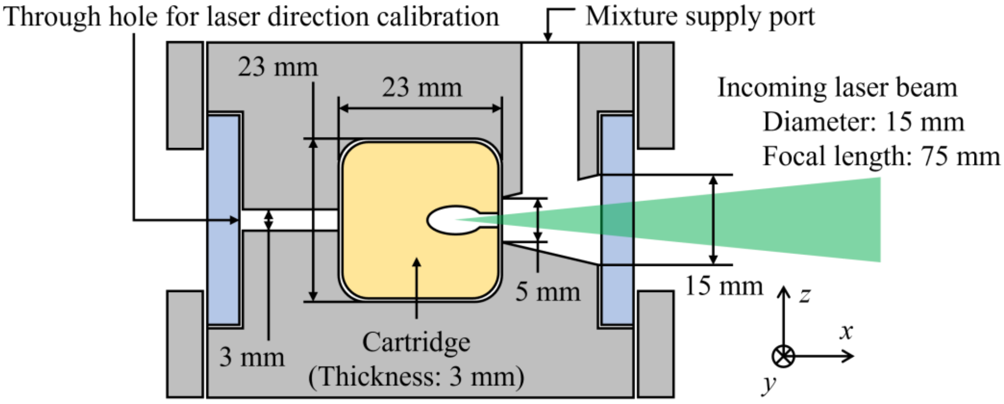

Figure 1: Cross section of the combustor.
The ignition laser comes from the right side and enters the cavity.

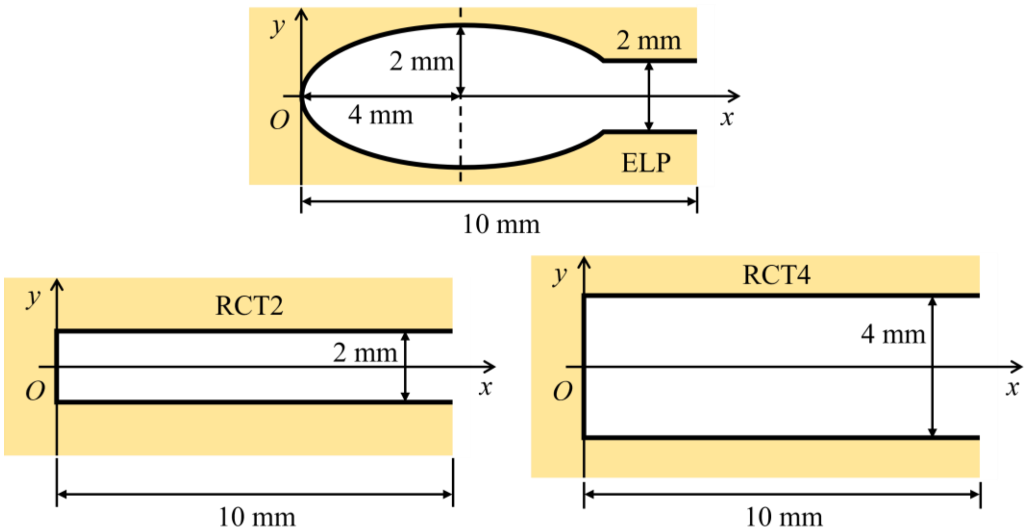

Figure 2: Variety of the cavity with a coordinate system to calculate the Mach number change.
Ellipse – rectangular cavity is ELP (top), and rectangular cavities are RCT series (bottom).

Figure 3 shows the optical systems for laser ignition and schlieren visualization. All the optomechanical products for laser ignition are connected to the combustor to fix the focal point. For the ignition source, Nd:YAG laser (wavelength: 1064 nm; emission energy: 200 mJ; emission time or full width at half maximum: 5.0 ns) was used. The final input diameter was 15 mm, and an aspheric lens (focal length: 75 mm) was used to condense the beam.

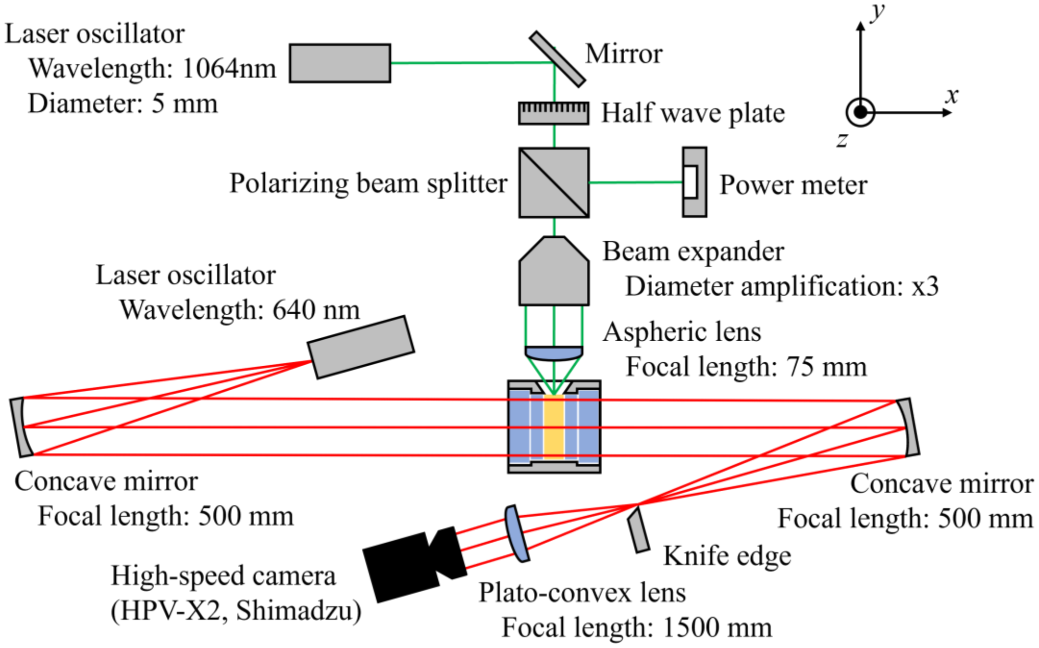

Figure 3: Top view of the optical systems.
The optical system for laser ignition (green) and for flowfield visualization (red).

The experimental condition is as follows: static, pre-mixed, stoichiometric C_2H_4 – O_2 mixture at 100 kPa was used. As for the igniting laser beam, Nd:YAG laser was used (wavelength: 1064 nm; emission time or full width at half maximum: 5.0 ns; input diameter 15 mm; focal length 75 mm; emission energy: 200 mJ). The recording was conducted at 100 ns/frame with 20 ns exposure time.

3 Results

Figure 4 shows the successive schlieren images of the flowfield. The first image which observed plasma generation is defined as t = 0 μs. In all the cases, a spherical initial shock wave (ISW) was observed, and especially in ELP, there was a concave reflected shock wave (RSW) following ISW. Since ISW propagates three-dimensionally, a convex line appeared in all cases from t = 1.3 to 1.8 μs. At t = 1.8 μs, local explosions occurred on the cavity wall in ELP. Though a spherical ISW was observed in RCT2 and RCT4 as well, there was no RSW as well as local explosions. Instead, Mach stems were observed in these cases at t = 1.8 and 2.8 μs respectively. In ELP, since the local explosion made a strong impact on the visualization windows, a planar acoustic wave was observed at t = 2.3 μs. In addition, the local explosions caused combustion waves to propagate from the upper and lower wall. While these combustion waves had covered up ISW from t = 1.8 to 3.8 μs, the triple points moved toward the x axis to collide at t = 3.8 μs where detonation was initiated at x = 5.5 mm. Though the detonation wave was initially concave, it deformed into a plane after it enter the rectangular section. Behind the detonation wave, a bow-shaped unburned gas pocket and three transverse waves could be observed at t = 4.3 and 4.8 μs. The gas pocket moved in the positive x direction due to the induced flow of the detonation wave, and it broke up into two as time goes making compression waves that propagate in the negative x direction at t = 4.8 μs.

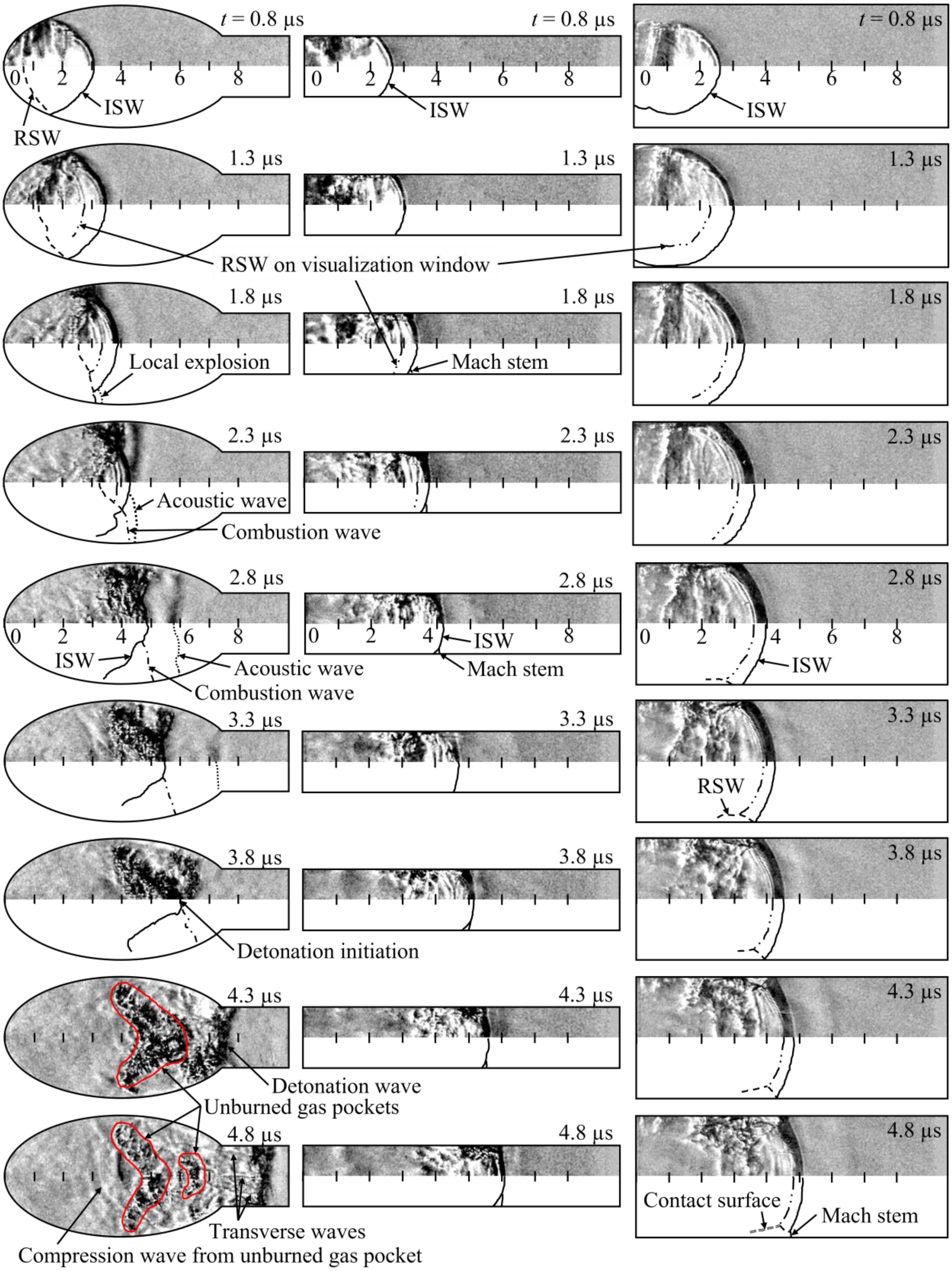

Figure 4: Successive schlieren images of the flowfield in ELP (left), RCT2 (center), and RCT4 (right). $t = 0$ μs is defined as the timing when the plasma was observed.

4 Analysis

Figure 5 shows the $x - t$ diagram on the x axis in ELP. At the early stage, from $x = 0$ to 6 mm, ISW propagated in the positive x direction, and a wave propagating at 2844 m/s appeared at $x = 4.5$ mm as seen in figure 4. Because the velocity of the acoustic wave in an acrylic plate is 2730 m/s, this wave was identified as an acoustic wave propagating in the visualization window. The detonation initiation occurred at $x = 6$ mm where the inclination of ISW got smaller, and at least four compression waves were observed propagating negative x direction from the unburned gas pockets.

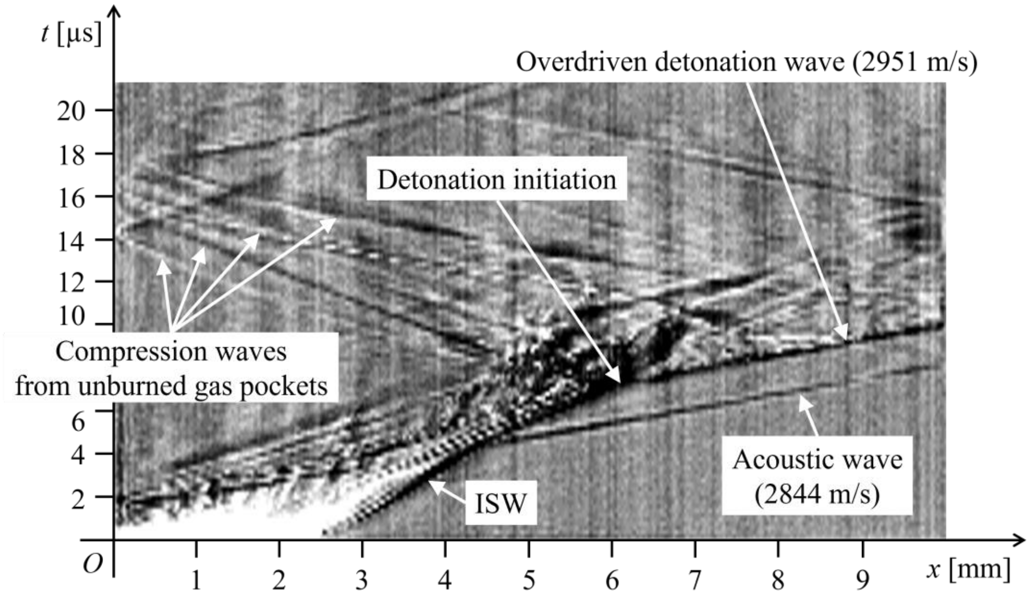

Figure 5: $x - t$ diagram on the x axis in ELP.

5 Discussions

Figure 6 shows the Mach number, M_x, versus the displacement, x, of the leading shock or combustion wave on the x axis defined in figure 2. Despite the cavity shape differences, the Mach number changes have mainly two common phases: deceleration and acceleration. After the laser irradiation, ISW's Mach number was $M_x = 3$ to 3.5, however, it dropped to $M_x = 2$ to 2.5 when $x = 4$ to 5 mm, which is equivalent to $t = 1.8$, 2.8, and 4.8 μs in ELP, RCT2, and RCT4, respectively in figure 4. Considering that ISW appeared to expand three-dimensionally in schlieren images and that the deceleration phase appeared in all cases, this rapid decrease was due to the expansion regime behind ISW, in other words, due to the gasdynamic effect. However, though ELP and RCT2 ended the deceleration at $x = 4$ mm, RCT4 ended it at $x = 5$ mm, which implies that the minimum cavity height limits the ISW's expansion and lets it accelerate earlier.

After the deceleration process, the Mach number increased in all the cases, specifically in ELP. In this case, the Mach number drastically rose to reach $M_x = 4$, and after a small constant phase, it started rising again going over the Chapman – Jouguet detonation Mach number, $M_x = 7.3$, which indicates that an overdriven detonation was initiated. Since the Mach number started to decrease gradually after reaching $M_x = 10$, it would asymptote to M_{CJ} eventually forming a planar self-sustained detonation wave. In the other cases, for example in RCT2, though the Mach number increased at the same timing as ELP, it stopped at $M_x = 3$ and remained constant. Despite the difference in timing, this behavior could be seen in RCT4 as well. Furthermore, since RCT2's Mach number began to increase at $x = 8$ mm, the classical DDT is ongoing in the acceleration process of the RCT series.

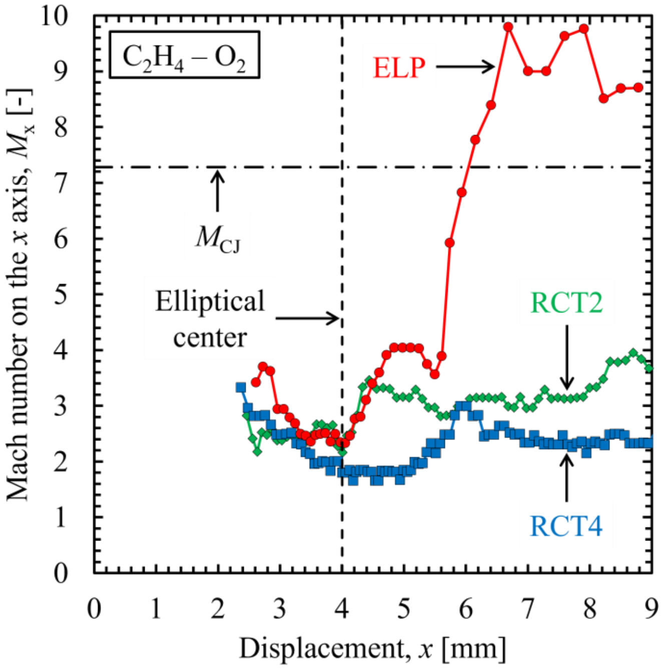

Figure 6: Mach number of the leading waves (incident shock wave or combustion wave) on the *x* axis versus thier displacement.

6 Conclusion

Detonation initiation was demonstrated by the combination of laser ignition and shock focusing, and an overdriven detonation was initiated successfully. Based on the schlieren images of the flow field, the initiation occurred in the following scenario. First, local explosions occurred near the upper/lower cavity wall. Second, combustion waves rapidly expanded to cover up ISW. Third, another local explosion occurred at the center line where triple points collided.

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