Experimental Study on Deflagration-to-Detonation Transition Shortening by Nanosecond Pulsed Laser Ignition

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1 Background

Pulse Detonation Combustor (PDC) generates detonation waves intermittently and is expected to be applied for various fields such as rocket engines and satellite thrusters [1]. PDC basically has four phases to gain thrust: fulfilling of a combustible gas mixture, ignition and Deflagration-to-Detonation Transition (DDT) process, propagation of detonation wave, and exhaust gas purging [1]. Since one cycle generates thrust once, the operation frequency ought to be maximized. According to Watanabe et al. [2], the frequency depends on the inverse of the combustor length, so the combustor length should be shorter for higher operating frequency. However, the combustor length cannot be smaller than the DDT distance, shortening DDT directly contributes to the minimization of the combustor and maximization of operation frequency.

Laser ignition is an ignition method in which high power laser is focused to cause laser breakdown and generate plasma to start combustion. This method is expected to be a breakthrough of DDT shortening. This is because, compared with spark-plug ignition, the focused laser has higher energy density [3], higher ignition probability in high-pressure gases [4], doesn't have either heat loss or erosion of the electrode, and has a higher spatial degree of freedom for ignition. Previous studies on laser ignition revealed the process of laser-induced breakdown [5] and sought minimum energy for breakdown and ignition [4, 6]. The characteristics of laser ignition have been researched so far. For example, Morgan [5] clarified the breakdown mechanism, Kopeceka et al. [4] examined minimum energy necessary for breakdown and ignition probability under different gas pressure, and Phuoc [6] revealed the minimum energy necessary for ignition. Furthermore, Endo et al. [3] conducted comparative ignition experiments using laser and a spark-plug to show that flame propagation is earlier in laser ignition.

Since fast flame propagation contributes for an early transition to detonation wave, laser ignition seems to be able to shorten DDT distance. Still, the factor and the mechanism of why fast flame propagation occurs are not clear. Therefore, in this paper, characteristics of laser ignition especially the blast wave formed by a breakdown and the freedom of ignition position are focused. First of all, the characteristics of the variable beam splitter are evaluated, and a blast wave after the breakdown is observed by the Schlieren method. Secondly, ignition experiments are conducted changing the focal point and the initial gas pressure to clarify how the mentioned factors affect the DDT process.

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2 Arrangement of Experiment Equipment and Experimental Conditions

Fig. 1 shows the optical system which can adjust the emission energy, E_P to occur laser breakdown. An Nd: YAG laser (Tempest 10, New Wave Research) emits 1064 nm wavelength, 5.0±0.3 pulse width, 5 mm diameter laser beam. Reflected once by a mirror, the beam's polarization is changed by the half-wave plate (HWP) and separated to P and S polarizations by a polarizing beam splitter. The P polarization beam goes to beam expander (BE03-1064, Thorlabs) whose expansion rate is fixed at 3. After being expanded, the beam is focused by an aspheric lens whose effective focal length (EFL) is 50 mm. The breakdown is observed at the focal point by a high-speed camera (HPV-1, Shimadzu) and by Schlieren method. By rotating HWP and changing its scale, θ_{scale}, the ratio of P and S polarizations are adjusted, and E_P will also be adjusted. The emission energy, E_P, is measured before the recording experiments using an energy detector (QE25LP-H-MB-QED, Gentec-EO). The experiments were conducted in the air at 295.95 K.

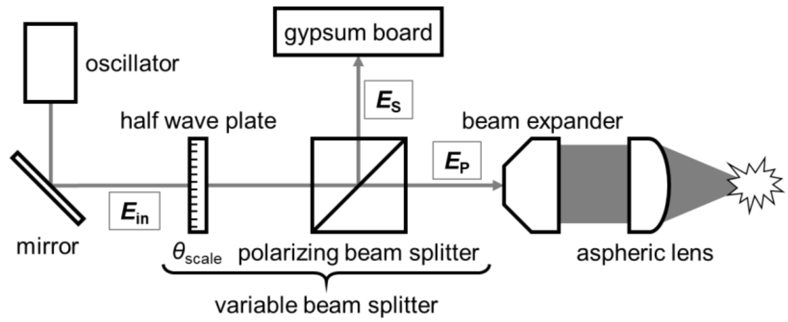

Fig. 1. The optical system to observe laser breakdown

Fig. 2 shows the cross section of the combustor used in laser ignition experiment. The combustor is made of SUS304, and its cross area is 10 mm square. And, two sides out of four walls are acrylic plate used as a visualization window for Schlieren method. There is a cellophane membrane at the end of right-hand direction to hold ethylene – oxygen mixture inside the combustor. In addition, for the laser beam's incident, an adapter in Fig. 3 is attached on the combustor. After being attached, the edge surface of the adapter becomes flush with the wall of the combustor.

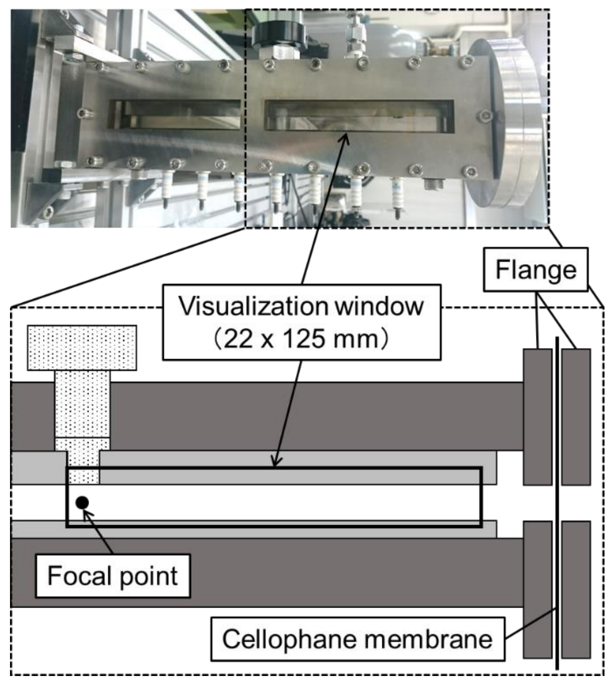

Fig. 2. The cut image of pulse detonation combustor

Table 1 shows the experimental condition. In all the cases, pre-mixed, stoichiometric, static $C_2H_4 - O_2$ gas was used, and the laser emission energy was at 216 mJ. Condition S1 is the standard with the gas pressure at 98 kPa and with the focal point at the center. Condition S2 has almost the same pressure at 100 kPa, but the focal point is set on the wall. Condition S3 has higher

Table 1. Experimental conditions

	S1	S2	S3
Gas	$C_2H_4 - O_2$ (pre-mixed, stoichiometric)		
Initial pressure [kPa]	98	100	125
Emission energy [mJ]	216		
Focal point (x, y) [mm]	center (0, 5)	wall (0, 0)	center (0, 5)
Frame rate	500,000 fps (2 μs/frame)		

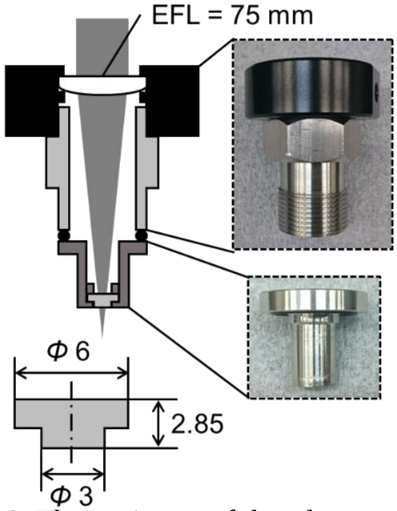

Fig. 3. The cut image of the adapter to fix lens and sapphire glass onto the combustor

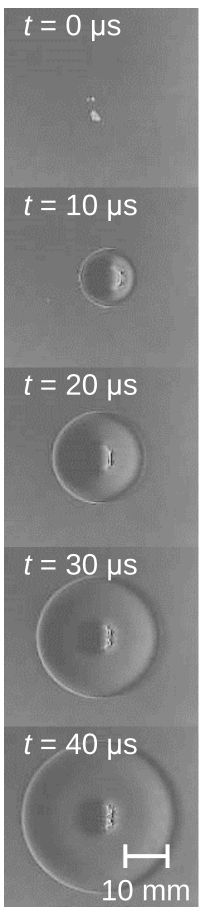

Fig. 5. The blast wave expansion process

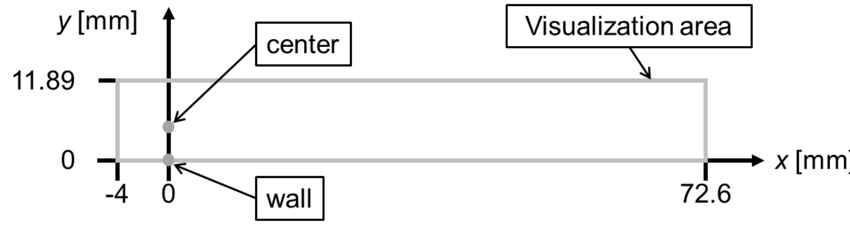

Fig. 4. The coordinate system to define ignition position

pressure at 125 kPa, and the focal point is set at the center of the combustor. The coordinates of focal points in Table 1 are defined by the coordinate system in Fig. 4. The recording was conducted by Schlieren method with the frame rate at 2 μs/frame.

3 Results and Discussions

Fig. 5 shows the blast wave propagation process recorded by the optical system in Fig. 1 when E_P was 140.4 mJ. After the flash defined as t = 0 μs, a spherical blast wave propagating from the focal point was observed. As in Fig. 6, from the points of each edge which the blast wave reaches first, a polar coordinates system is defined to measure the radius of the blast wave, R_S. Fig. 7 shows the time history of R_S. Plots indicate the experimental value, and the curves indicate extrapolated model equation (1) which derives from Taylor's blast wave theory considering time t as an explicit variable.

$$R_S = At^B \tag{1}$$

Constant numbers A and B are optimized in each curve by the coefficient of determination R^2 in the regime of R_S = 0 ~ 5 mm. Fig. 7 indicates that bigger beam energy leads to faster expansion of the blast wave. From Fig. 7, blast wave Mach number, M_S is calculated and expressed in Fig. 8. Plots indicate the average experimental value calculated from two points in Fig. 7 and the curves indicate a model equation (2) which is obtained by differentiating the equation (1) with respect to time, t.

$$M_S = \frac{A^{\frac{1}{B}}B}{a_0} {R_S}^{1-\frac{1}{B}} \tag{2}$$

The symbol a_0 in equation (2) means the speed of sound which is 345.2 m/s in the experiment. Fig. 8 indicates that the highest Mach number is 2.31 when E_P = 140.4 mJ, and the bigger beam energy provides a higher Mach number.

Fig. 9 shows the flame propagation process in experiment S1. Taking $t = 0$ µs at the frame when the ignition flash was observed, a spherical flame kernel was observed at the focal point (at the center of the combustor) at $t = 10$ µs. This kernel had propagated producing shock waves in its front and formed like a tulip which is unique to DDT process at $t = 90$ µs. Finally, a local explosion occurred near the wall at $t = 120$ µs. Based on Fig. 9, an $x - t$ diagram at $y = 0$ is shown in Fig. 10. As is often observed and explained in the DDT process, the flame front had accelerated gradually producing three shock waves until a local explosion occurred.

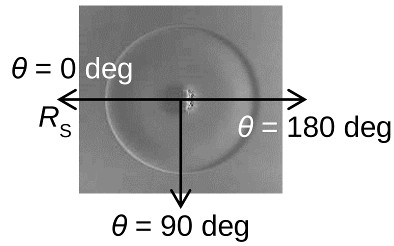

Fig. 6. The polar coordinates to measure the blast wave radius

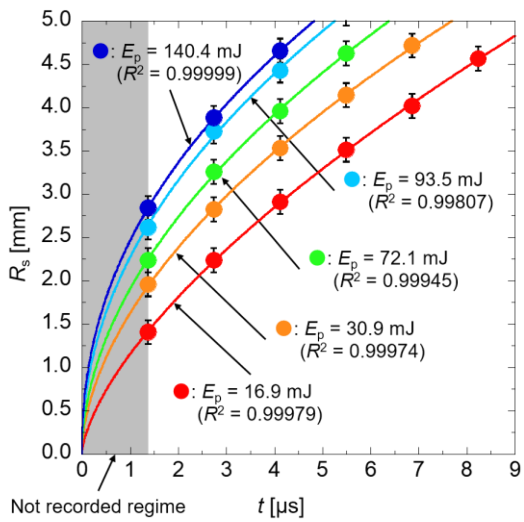

Fig. 7. Time history of the blast wave radius

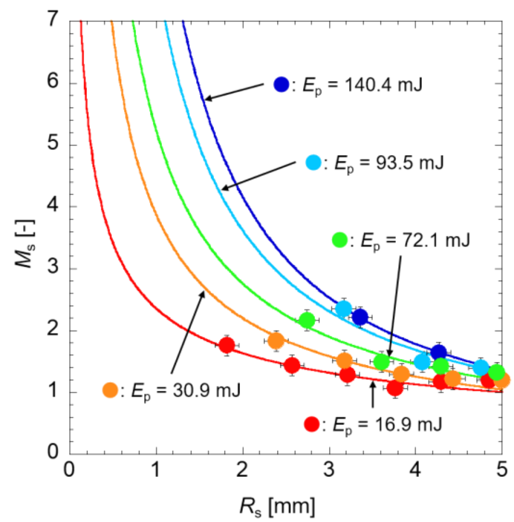

Fig. 8. Blast wave's Mach number change

Calculating 11 point average from the flame front position in $x - t$ diagrams of S1, S2 and S3, the velocity change of the flame front is compared in Fig. 11. Comparing S1 and S2 which are different in ignition position, the average velocity of S2 is 6.75% smaller than that of S1, and the frequency of local flame acceleration is also low. On the other hand, comparing S1 and S3 which are different in the initial pressure, the average velocity of S3 is 22.8% higher than that of S1, but the frequency of local flame acceleration is almost the same.

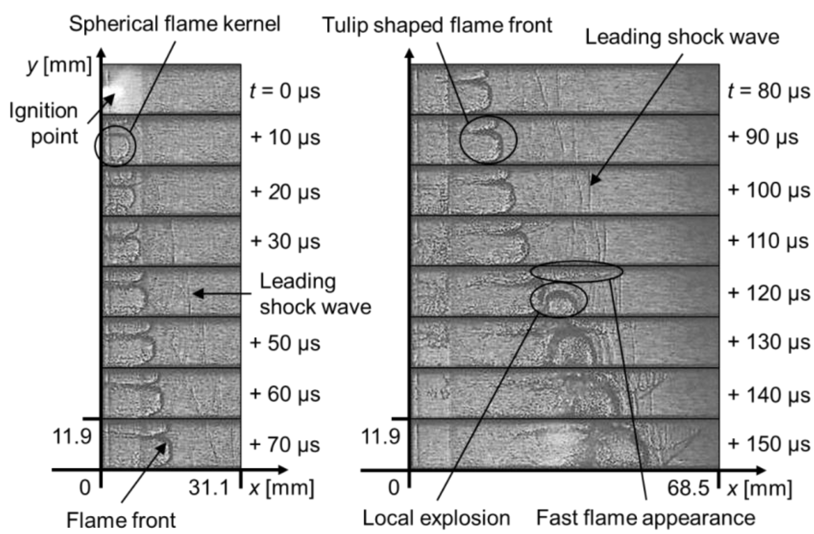

Fig. 9. Propagation process of the flame front and the shock wave caused after the laser emission

In order to clarify the cause for these differences, the area near the ignition position is focused in Fig. 12. In S1, flame kernels are formed at the center and on the wall of the combustor, and shock waves propagate in a positive way of x-axis reflecting repeatedly on the walls.

But in S2, though shock waves propagate and reflect, there is no area where shock waves jumble in front of the flame. In S3, the area includes more jumbled shock waves than in S1 at $t = 40$ μs, and it is expected that turbulence is induced in this area. In the DDT process, turbulence in front of the flame contributes to the flame front deformation and increase of the flame front area. These changes lead to more heat transfer from the flame to the unburned, compressed gas and lead to compression wave production. The more compression waves are produced, the higher the velocity after the waves will be, and the flame can accelerate by the flow. So, the reason why local flame acceleration occurred more frequently in S1 and S3 and why the average velocity is comparatively high in these cases is because a shock wave produced after ignition reflected and form a turbulent area.

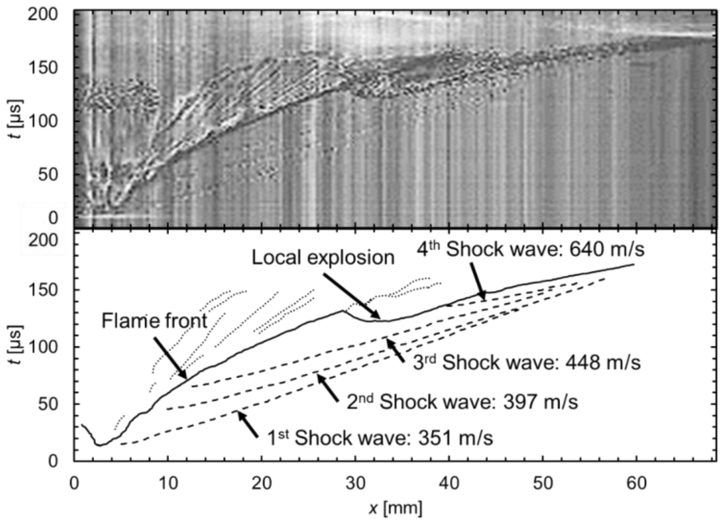

Fig. 10. The $x – t$ diagram at $y = 0$, a flame acceleration providing four shock waves was observed

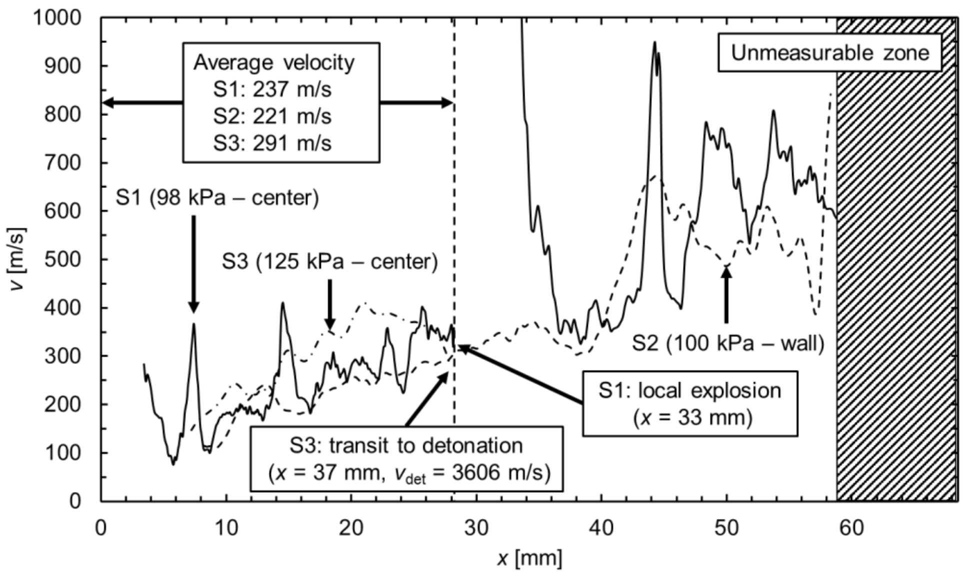

Fig. 11. The $v – x$ diagram at $y = 0$, local flame accelerations occur more frequently with its ignition position at center and with higher initial pressure

Conclusion

Laser breakdowns by different emission energies were observed using Schlieren visualization method, and the time history of blast wave radius and Mach number was clarified. The highest Mach number was

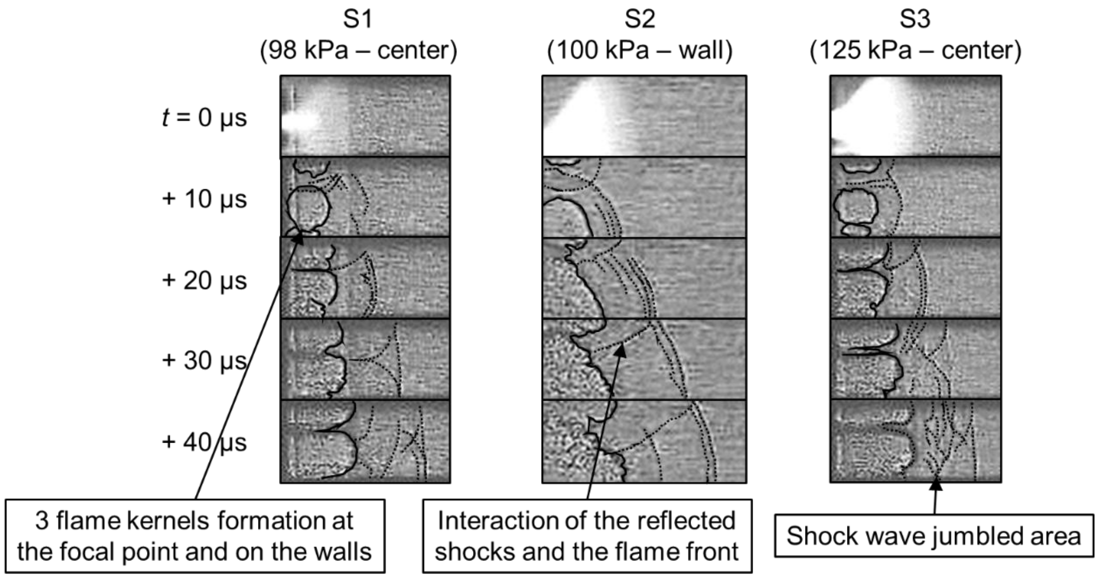

Fig. 12. The focused images of the ignition position from t = 0 – 40 μs. Igniting at center in higher pressure gas leads to more jumbled shock wave area.

calculated to be 2.31, and it gets larger following the emission energy. Also, three ignition experiments were conducted changing the ignition position and the initial gas pressure. It is found that ignition at the center of the combustor in higher initial pressure can induce a turbulent area of reflected shock waves and this contributes for higher average flame velocity by 6.75 to 22. 8% and higher frequency of local flame acceleration.

Acknowledgment

This work is supported by a Grant-in-Aid for Young Scientists (A) (No. 17H04971).

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