Influence of gradual expanding channel cutoff on propagation of the toroidal detonation wave

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1 Introduction

A pulse detonation engine (PDE), in which a propellant burns in detonation waves intermittently, has attracted the attention of researchers because of its simplicity and theoretically higher thermal efficiency [1-4]. The major issue that needs to be resolved for the practical use of a PDE is the "detonation initiation." To initiate a detonation wave using a typical energy source, the authors have proposed a combination method involving a "predetonator," "reflector," and the "overfilling of the driver gas mixture," as shown in Fig. 1 [5-7]. The detonation wave propagates around the reflector, which changes the wave shape through three transition stages, as suggested in Fig. 1: from planar (A) to cylindrical (B), toroidal (C), and back to planar (D) again. Wakita et al. [6] showed that the successful transition to a toroidal detonation wave (C) is accomplished by filling 30 mm of the upper streams of the detonation chamber with the driver gas mixture. Our reflector uses a conical part to accomplish the successful transition from the toroidal detonation wave (C) to the planar detonation wave (D) without quenching, as shown Fig. 1. Wakita et al. [7] investigated toroidal detonation wave propagation through the gradually expanding channel around the conical part in nitrogen-diluted stoichiometric H_2-O_2 mixtures. Figure 2 shows the dependence of the ratio of the annular gap width to the cell size of the detonation waves (L/λ) on the detonation transition. The open symbols represent "Go" cases, and the solid symbols represent "Nogo" cases. The "Go" is the case that the toroidal detonation wave (C) does not quench at a convex corner of the entrance of the conical part and smoothly transmit to the planar detonation wave (D). In contrast, the "Nogo" is the case that a temporal quenching was observed at the convex corner. Note that successful transition to the planar detonation wave (D) was confirmed downstream of the detonation chamber for all of the conditions examined. That is, the difference between "Go" and "Nogo" is whether the temporal quenching was observed or not. When the angle of the expanding channel, α, is greater than 30°, the threshold value of L/λ is approximately 4, which is the same as the value at 90°. That is, when the half angle of the conical part is larger than 30°, it has no effect to prevent the temporal quenching. On the other hand, the promotion effect obtained by a conical body of 15° is extremely high, and the threshold value is approximately 2.

Since the conical angle by which propagation of a detonation wave is promoted is shallow, as the previous studies show, a conical part becomes very long and heavy. The objective of this report is to find out the path width L' at which the conical part can be cutoff without performance decrement, as

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shown in Fig. 3. We can expect that the path width at which the conical part can be cut down is 4 times of the cell size λ, because the threshold value of L/λ is approximately 4 when we use the cylinder part only.

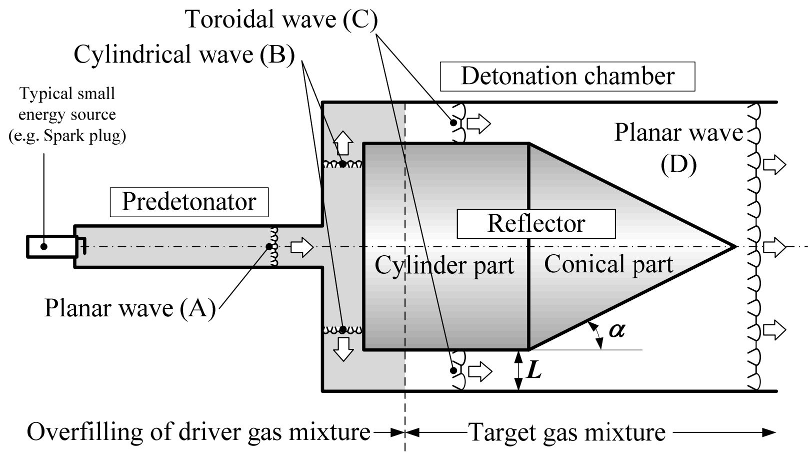

Figure 1. Combination detonation initiation method of a “predetonator”, a “reflector” and “overfilling” of driver gas mixture.

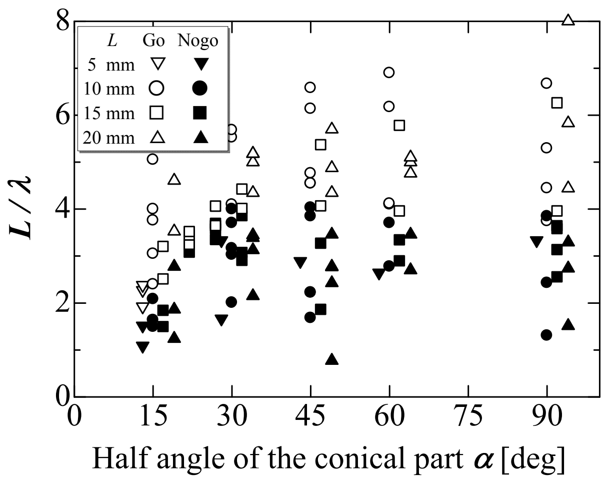

Figure 2. Combination detonation initiation method of a “predetonator”, a “reflector” and “overfilling” of driver gas mixture.

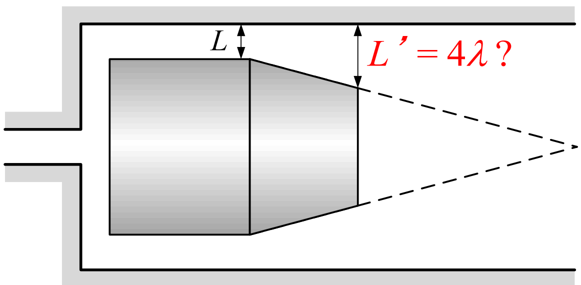

Figure 3. Path width L' at which the conical part can be cut down without performance decrement.

2 Experimental Set-up

Figure 4 shows a schematic of the experimental apparatus and a whole picture of the reflector. The experimental apparatus consists mainly of a detonation chamber, a predetonator and the reflector. The detonation chamber is 620 mm long, with an internal diameter of 100 mm. The predetonator length from the ball valve to the predetonator exit is 215 mm, with an internal diameter *d* of 20.4 mm. This length is sufficiently greater than the DDT length of a stoichiometric hydrogen–oxygen mixture for this tube diameter. The reflector consists of a cylinder part and a frustum of circular cone, and is connected with an upper flange of the chamber by four M6 support shafts. The annular gap width *L* between the cylinder body and the sidewall of the detonation chamber is set at 10 mm. A distance from the predetonator exit to the upstream surface of the cylinder part is chosen to be 10 mm. The half angles of the conical body α are 10°, 15° and 20°. Path widths at the cutoff position of the conical part *L'* are summarized in Table 1.

Detonation wave was detected by velocity measurements and soot foil records. Pressure histories were obtained at M1–M4. Soot foils collected at the three locations shown in Fig. 4—I: a surface of the cylinder part, II: a surface of the detonation chamber, and III: a frustum of circular cone. The cell size was measured at 10 mm upstream from the aft end of the annular path on the soot foil of the surface of the cylinder part (near the M2 position in Fig.4).

Detonation wave was initiated by an overfilling method of a driver gas mixture. To overfill the driver gas mixture in the combustion chamber, an additional volume was installed upstream of the predetonator, as shown in Fig. 4. This additional volume was a 20 mm I.D. tube, which was connected to the predetonator via a ball valve. Figure 5 shows the overfilling procedure. Initially, the valve was closed and the driver gas mixture and target gas mixture filled the upstream and downstream areas of the valve, respectively (Fig. 5-(A)). A gas-handling machine prepared and completely mixed these mixtures. The pressure of the driver gas, p_1, was higher than that of the target gas, p_2. When the valve opened (Fig. 5-(B)), the driver gas mixture overfilled the position *h* where the balance pressure p_3 was established. In all of the experiments, the balance pressure (initial pressure) was 1 atm. A control device determined the timing of the valve opening and ignition, and activated a spark plug 1 second after the valve opened. The authors chose a value of 30 mm for *h*. The driver-gas mixture was a stoichiometric hydrogen–oxygen mixture, and the target-gas mixtures were stoichiometric hydrogen–oxygen mixtures diluted with nitrogen.

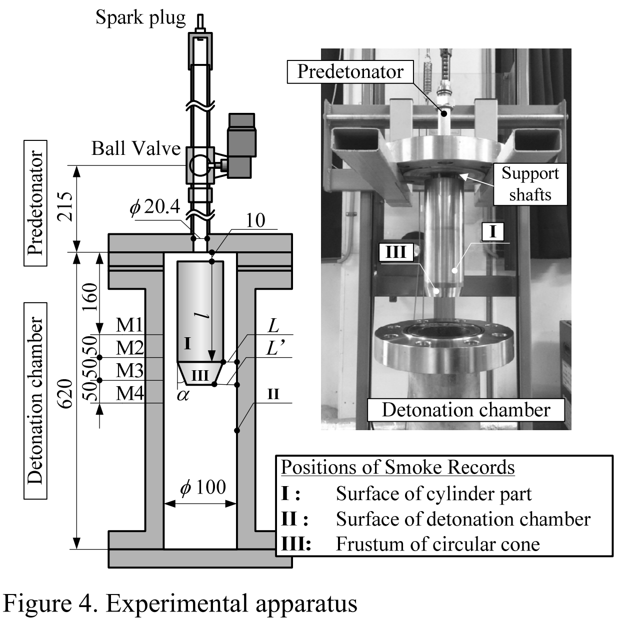

Figure 4. Experimental apparatus

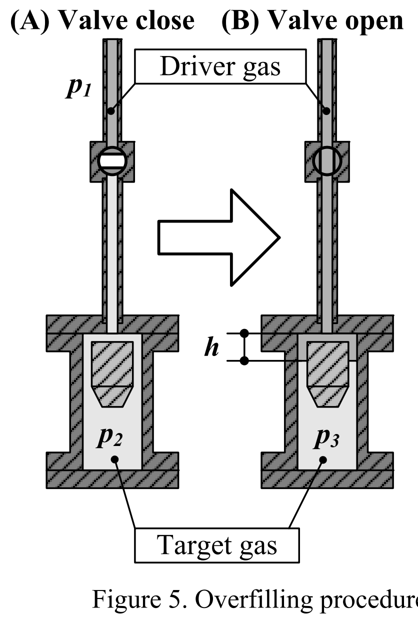

Figure 5. Overfilling procedure

Table 1: Path widths at the cutoff position of the conical part *L'*

Half angles of the conical body α [deg]	Path widths at the cutoff position of the conical part *L'* [mm]					
10	(10)		15	20	30	(50)
15	(10)	12.5	15	20		(50)
20	(10)	13		20		(50)

3 Results and Discussion

To investigate the variation of the toroidal detonation transition, a series of experiments with various nitrogen concentrations of the target gas mixture was performed and we categorized them into three patterns: A) Successful Transition (Go), B) Partially Successful Transition (Marginal) and C) Transition Failure (Nogo). Examples of these three patterns are shown in Fig. 6. Each example has a soot track image at the surface of the detonation chamber, pressure histories at M1 to M4, and a table of velocity measurments between them. In the soot tracks, the toroidal detonation wave propagates from top down. White broken lines in the tracks indicate aft end position of the cylinder part of the reflector. In the Go cases like Fig. 6-A), the wave velocity between M3 and M4 is more than 0.8-times theoretical CJ speed. We can observe an approximately-linear boundary on the soot track about 30 mm

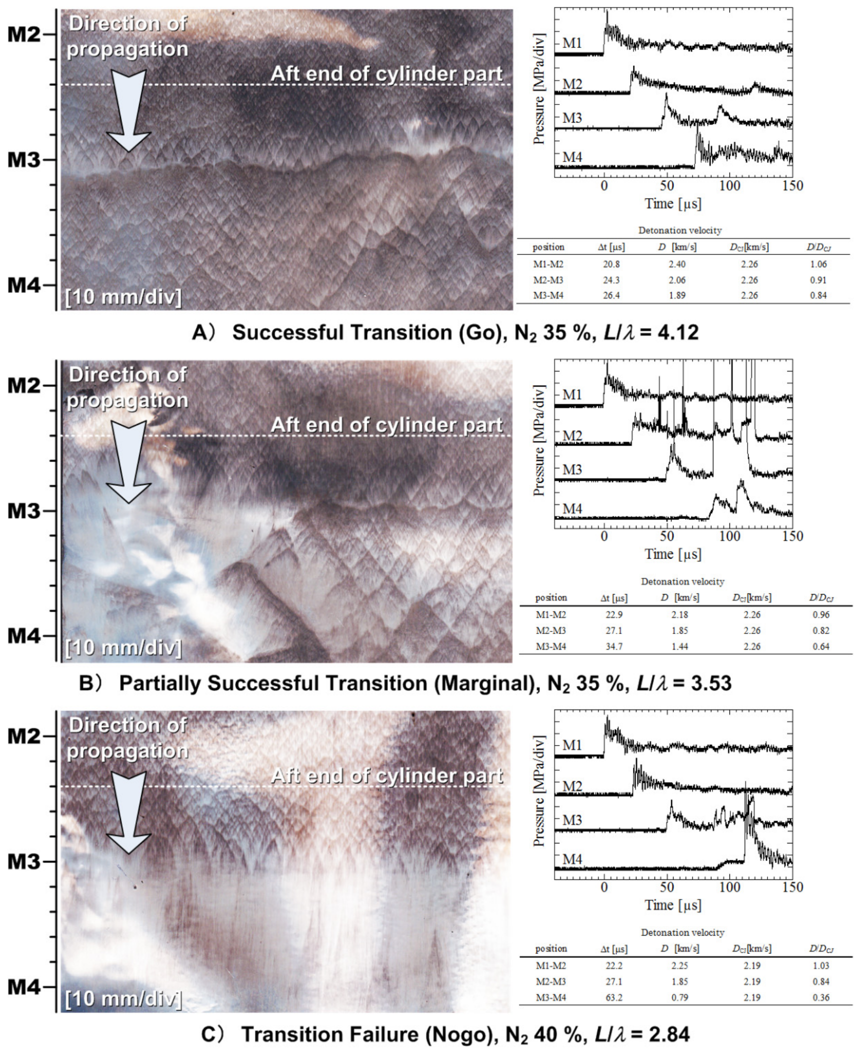

Figure 6. Examples of the toroidal detonation wave transition Go, Marginal and Nogo. (Soot tracks on the surface of detonation chamber, pressure histories and detonation velocities).

downstream of the white broken line (near the M3 port). This boundary indicates the position where the rarefaction wave from the aft end corner of the reflector reached the surface of the detonation chamber. In all cases that the toroidal detonation wave is quenched, it disappears on this boundary. When the velocity exceeds 0.8 time of CJ value, the toroidal wave propagate successfully at all domain of the boundary without quenching. In contrast, the velocity between M3-M4 is below 0.8 time of CJ value in the Marginal cases and the Nogo cases. But in the Marginal cases, the successful transition of the detonation wave is partially observed on a boundary shown in the track of Fig.6-B). It is Nogo when the detonation wave has disappeared completely on the boundary.

Figure 7 shows the kinds of transitions for various path widths at cutoff position with changing the nitrogen concentration: Open circles, half open circles and solid circles represent Go, Marginal, and Nogo, respectively, and the longitudinal and horizontal axes are the ratio of the annular gap width and cell size (L/λ) and the path width at cutoff position (L'), respectively. The leftmost line of each graph, in which the L' is 10 mm, shows the results of no frustum of circular cone part. In this case, the threshold value of L/λ between Go and Nogo is approximately 4, as shown in [6]. In contrast, the rightmost line of each graph, in which the L' is 50 mm, shows the results at the time of using full length cone part. The threshold values when L' = 50 mm, are different every angle, about 1 when α = 10°, about 2 when α = 15° and about 3 when α = 20°, as shown in [7]. The Present results show that threshold value L/λ of each cutoff position approaches the threshold values when L' is 50 mm, from 4 as the path width at the cutoff position becomes large. When experimental conditions are L' = 30 mm at α = 10°, L' = 20 mm at α = 15° and L' = 20 mm at α = 20°, threshold values are same to L' = 50 mm at each angles. That is, these results indicate that even if the cone part was cut, the cutoff reflector has same effect as the traditional cone reflector and leads also to weight reduction in several conditions. However, excessively short frustum of circular cone parts do not have similar propagation enhanced effect like full length cone parts.

In order to confirm the hypothesis that the path width at which the conical part can be cut down is 4 times of the cell size λ, we reevaluated the results of Fig. 7 by the ratio of the path width at the cutoff position and cell size (L'/λ), as shown in Fig. 8. The longitudinal axis was changed from the ratio of the annular gap width and cell size (L/λ) to the ratio of the path width at the cutoff position and cell size (L'/λ). The broken line indicate L'/λ = 4. Figure 8 shows that threshold values of excessively short frustum of circular cone parts are L'/λ= 4. Although the marginal case is observed near the threshold values, it is mostly in agreement with a hypothesis at every angle. It means that cone parts cut at the position which L'/λ is larger than 4, the cutoff reflector has same effect as the traditional cone reflector.

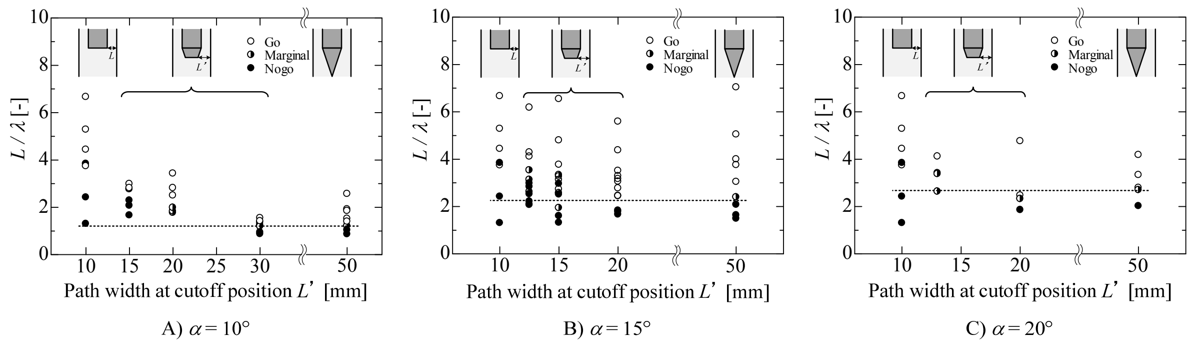

Figure 7. Kinds of transitions vs the ratio of the annular gap width and cell size (L/λ).

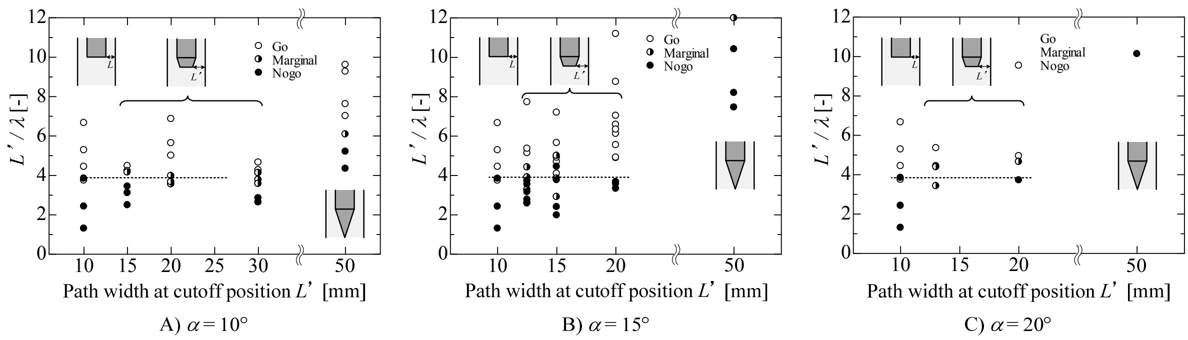

Figure 8. Kinds of transitions vs the ratio of the annular gap width and cell size (*L'/λ*).

4 Conclusions

We have emplpyed a reflector, which consists of a cylinder part and a conical part, to achieve reliable transmission of detonation wave for a pulse detonation engine (PDE) combustor. In this study, we investigated the influence of the conical part, which was cut for weight saving, on toroidal detonation wave propagation. A series of experiments find out the path width at which the conical part can be cut down without performance decrement, and confirm our hypothesis that the path width at which the conical part can be cut down is 4 times of the cell size *λ*.

Acknowledgments

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