Effects of diluent gas on toroidal detonation wave propagation through gradual expanding channel

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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." When a PDE operates in the air-breathing mode, the combustible gas is likely to be a fuel-air mixture and its detonation sensitivity—the ability to initiate the detonation of the combustible mixture—is lower than that of fuel–oxygen mixtures [5]. Another case where the sensitivity may be low is when the fuel is in the liquid phase. The energy required to initiate detonation with low-sensitivity propellants such as the fuel–air mixture and liquid phase mixture mentioned above is too large to directly initiate a detonation wave using the commonly employed energy sources [4].

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 [6, 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. [7] 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. [8] 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 ($\boldsymbol{L/\lambda}$) on the detonation transition. The open symbols represent "Go" cases, and the solid symbols represent "No Go" cases. Strict definitions of the "Go" and "No Go" cases are given in the "Results and Discussion" section. When the angle of the expanding channel, $\boldsymbol{\alpha}$, is greater than 30°, the threshold value of $\boldsymbol{L/\lambda}$ is approximately 4, which is the same as the value at 90°. On the other hand, the promotion effect obtained by a conical body of 15° is extremely high, and the threshold value is approximately 2. Figure 3 shows a 2D conceptual diagram of the transition of the toroidal detonation at the expanding channel. The heavy broken line **A** in Fig. 3 shows the head of the transverse shock (the same as the trajectory of the triple point), which is the first wave to reach the conical body. This transverse wave would reflect to **B** when the wall angle is smaller than the angle of the triple-point trajectory, such as with a 15° wall. In practice, the toroidal detonation wave has a three-dimensional structure, and the transverse shocks interact with each other in a circumferential direction. However, it is thought that the traverse waves that propagate in planes perpendicular to the direction of a detonation wave are mainly influenced by the conical part. Accordingly, the reflection of the transverse shock in this plane on the upstream side of the conical body plays an important role in promoting the detonation transition when the conical angle is small.

Until this point, we only employed nitrogen-diluted target-gas mixtures. Here, we used argon-diluted stoichiometric H_2-O_2 mixtures as target gases to confirm the generality of the toroidal detonation wave propagation through a gradually expanding channel.

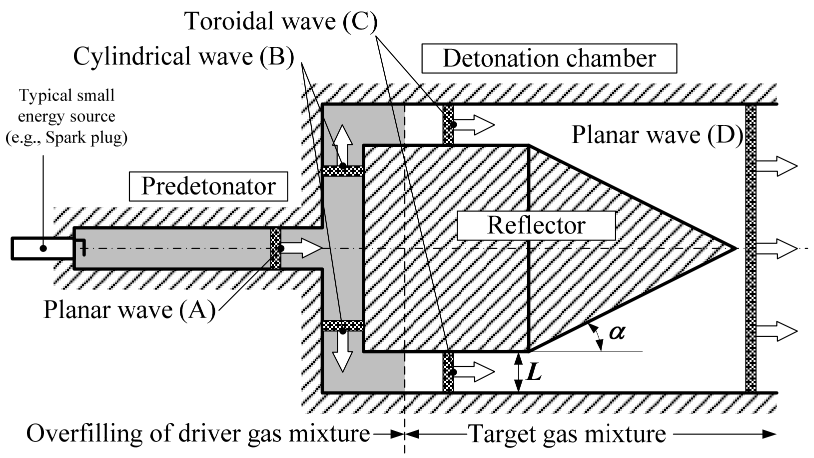

Figure 1. Combination detonation initiation method using “predetonator,” “reflector,” and “overfilling” of driver gas mixture.

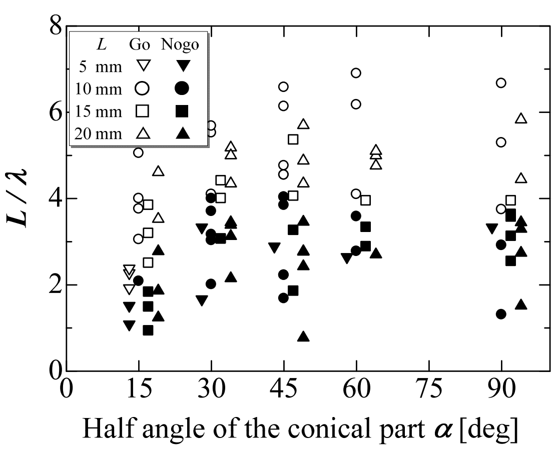

Figure 2. Transition status for nitrogen-dilution case [8].

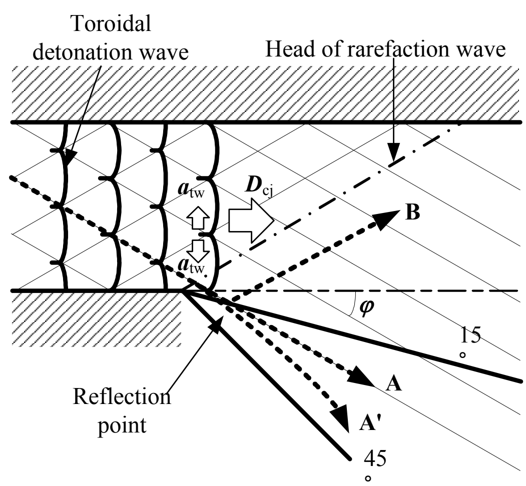

Figure 3. 2D conceptual diagram of transition of planar toroidal detonation at convex corner [8].

2 Experimental details

Figure 4 shows a schematic of the experimental apparatus. It consists mainly of a detonation chamber and a predetonator. 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 260 mm, with an internal diameter $\boldsymbol{d}$ of 20.4 mm. This length is sufficiently greater than the DDT length of a stoichiometric hydrogen–oxygen mixture for this tube diameter. Four M6 shafts support the reflector, which consists of a cylinder body and a conical body. The length of the cylinder body $\boldsymbol{l}$ is 200 mm. The authors chose a value of 10 mm for the reflector clearance $\boldsymbol{w}$, which is the distance from the predetonator exit to the upstream surface of the cylinder body. The annular gap width $\boldsymbol{L}$ between the cylinder body and the sidewall of the detonation chamber is set at 15 mm. The half angle of the conical body $\boldsymbol{\alpha}$ varies from 15° to 90°.

The authors used an overfilling method to initiate a toroidal planar wave propagating along an annular path filled with the target gas. To overfill the driver gas 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, $\boldsymbol{p_1}$, was higher than that of the target gas, $\boldsymbol{p_2}$. When the valve opened (Fig. 5-(B)), the driver gas overfilled the position $\boldsymbol{h}$ where the balance pressure $\boldsymbol{p_3}$ 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 2 s after the valve opened. The authors chose a value of 30 mm for $\boldsymbol{h}$. The driver-gas mixture was a stoichiometric hydrogen–oxygen mixture, and the target-gas mixtures were stoichiometric hydrogen–oxygen mixtures diluted with argon.

Soot foils collected tracks of the triple points of the detonation waves at the three locations shown in Fig. 4—I: the sidewall of the detonation chamber, II: the sidewall of the cylinder body, and III: the sidewall of the conical body. The cell size was measured at 10 mm upstream from the aft end of the annular path on the soot foil of the sidewall of the cylinder body.

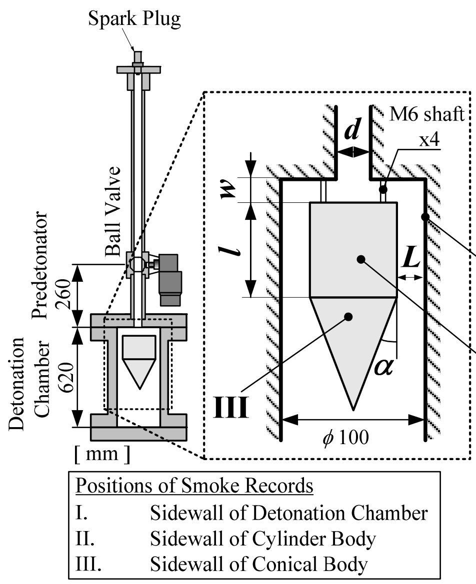

Figure 4. Experimental apparatus.

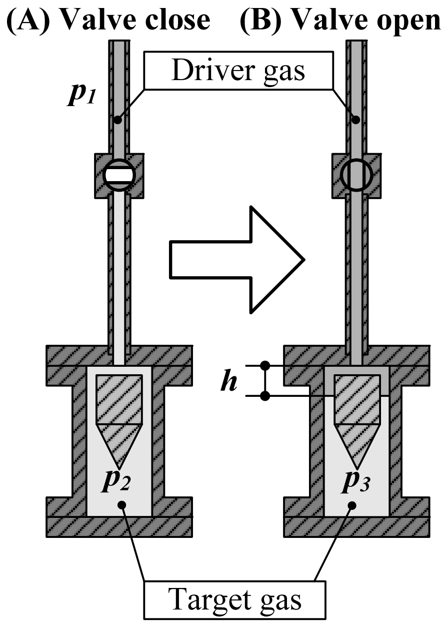

Figure 5. Overfilling procedure.

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3 Results and Discussion

Figure 6 shows the soot tracks of the detonation chamber with $\boldsymbol{L}$ = 15 mm and $\boldsymbol{\alpha}$ = 90°, meaning that the conical body was not used. The detonation wave travels from the left to the right. The broken line **A** shows the aft end of the cylinder body. The top track in Fig. 6 shows a “Go” case at **Ar** = 77.5%. Cellular structures covered the entire section of the surface, and no temporal quenching was observed. In contrast, the bottom track of Fig. 6 shows a “No Go” case at Ar = 80%. In this case, the cellular structure disappeared at line **A**. That is, the detonation wave was quenched by the expansion wave generated from the annular path exit. The authors defined the condition in which a temporal quenching like this was observed as a “No Go” case. Incidentally, even for the “No Go” condition, the re-initiation of the detonation wave was confirmed downstream of the detonation chamber, like at B in Fig. 6, for all of the conditions examined.

Figure 7 summarizes all of the experimental results, showing the dependence of the ratio of the annular gap width to the cell size of the detonation waves ($\boldsymbol{L}/\boldsymbol{\lambda}$) on the Go/No Go results. The longitudinal and horizontal axes are $\boldsymbol{L}/\boldsymbol{\lambda}$ and half angle $\boldsymbol{\alpha}$, respectively. Cell size $\boldsymbol{\lambda}$ of a detonation wave was measured at 10 mm upstream from the aft end of the cylinder body. In this report, the argon concentration range is 70% to 90%. If the argon concentration increases from 70% to 90%, the $\boldsymbol{L}/\boldsymbol{\lambda}$ ratio will decrease from about 7 to about 1.8 mm. The threshold value for the “Go” and “No Go” cases is approximately 4 at $\boldsymbol{\alpha}$ = 30°, 45°, 60°, or 90°. Accordingly, when the angle exceeds 30°, the conical body has no effect on the detonation transition enhancement. On the other hand, when the angle is less than 30°, the promotion effect becomes strong, and the threshold value decreases to approximately 2 when the angle is 15°. As in the critical tube diameter experiments, a propagation limit is generalized by the ratio of the characteristic length to the cell size in many cases. However, for a highly argon-diluted mixture, which has a highly regular cellular pattern, such a generalization may not be applied [9]. Nevertheless, the threshold values of $\boldsymbol{L}/\boldsymbol{\lambda}$ in the argon-dilution cases in our experiments were quite similar to those in the nitrogen-dilution cases.

As discussed in Fig. 3, the reflection of the transverse shock on the upstream side of the conical body might play an important role in promoting the detonation transition when the conical angle is small. The trajectory of the triple point **A** is at an angle $\boldsymbol{\varphi}$ to the traveling direction of the detonation wave. This angle was derived from the ratio of the transverse wave velocity $\boldsymbol{a}_{\mathrm{tw}}$ to the detonation wave velocity $\boldsymbol{D}_{\mathrm{CJ}}$. These velocities were calculated using the NASA computer program Chemical Equilibrium with Applications (CEA). Figure 8 shows the angles of the triple-point trajectory, $\boldsymbol{\varphi}$, for various dilution conditions. The black and gray symbols represent the argon-dilution case and nitrogen-dilution case, respectively. Under the argon conditions and nitrogen conditions, although there is some difference, it can be said that both of the triple-point trajectory angles were about 30°.

Figure 9 shows the soot tracks on the conical body sidewall with $\boldsymbol{\alpha}$ values of 20°, 30°, and 45° for Ar = 75%. The detonation wave travels from the left to the right. The circular arc of each soot track is a joint part of the aft end of a cylinder body. When the conical half angle $\boldsymbol{\alpha}$ was 20°, which was smaller than the angle of the trajectory of the triple point $\boldsymbol{\varphi}$ (about 30°), the detonation cellular structure was observed just behind the aft end of the cylinder body in the $\boldsymbol{\alpha}$ = 20° track. This is considered to be evidence that the transverse wave would reflect on the conical wall when the wall angle is smaller than the angle of the triple-point trajectory. On the other hand, when $\boldsymbol{\alpha}$ was 30°, which was the same as $\boldsymbol{\varphi}$, the structure was not observed just behind the cylinder body but was observed on the right side of broken line A. In this case, the triple-point trajectory became parallel to the conical wall; however, the triple-point trajectory became deeper than the initial angle (broken line A’ in Fig. 3) as the diffracted shock wave became weaker. Because of this, the transverse wave reflection on the conical wall occurred about 20 mm downstream from the aft end of the cylinder body. When $\boldsymbol{\alpha}$ was 45°, which was greater than the angle of the triple-point trajectory, the re-initiation broken line A moved further downstream. It is considered that this re-initiation was not because of the transverse wave reflection on the conical wall but because of the implosion of the toroidal shock wave transmitted from the toroidal detonation wave [8]. Note that the soot track that has a cell pattern just behind the aft end of the

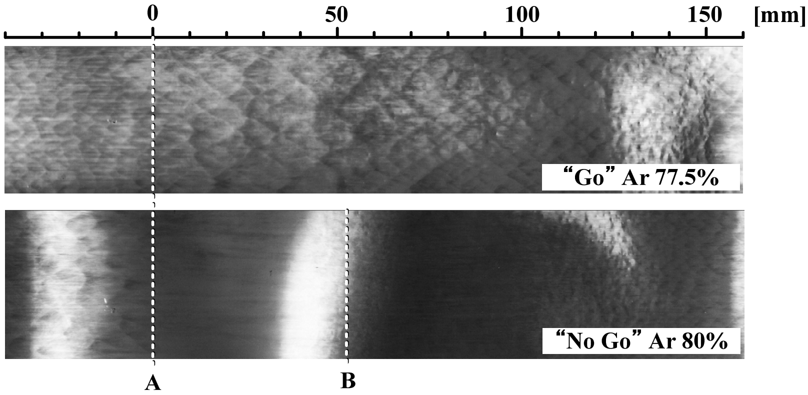

Figure 6. Soot tracks of detonation chamber sidewall under "Go" and "No Go" conditions at $\boldsymbol{L}$ = 15 mm and $\boldsymbol{\alpha}$ = 90°.

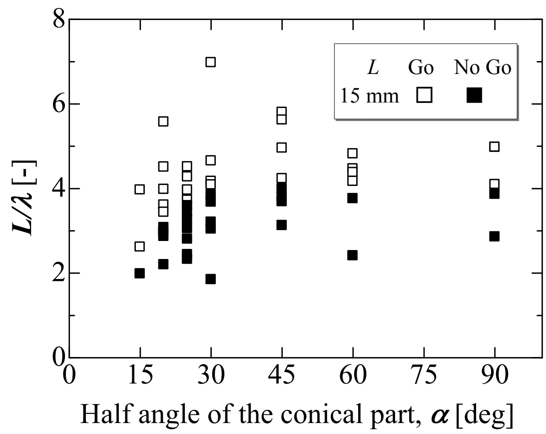

Figure 7. Transition status for argon-diluent case.

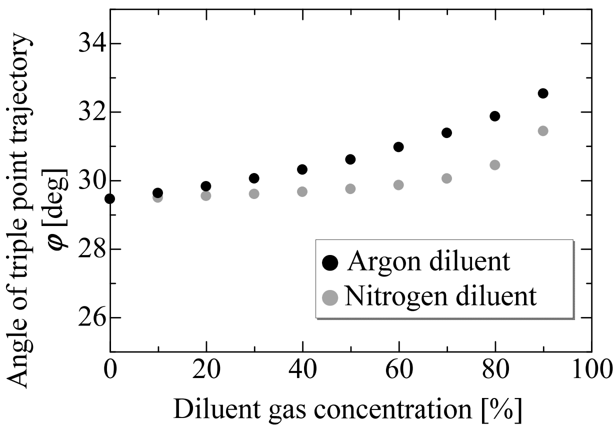

Figure 8. Angle of triple-point trajectory.

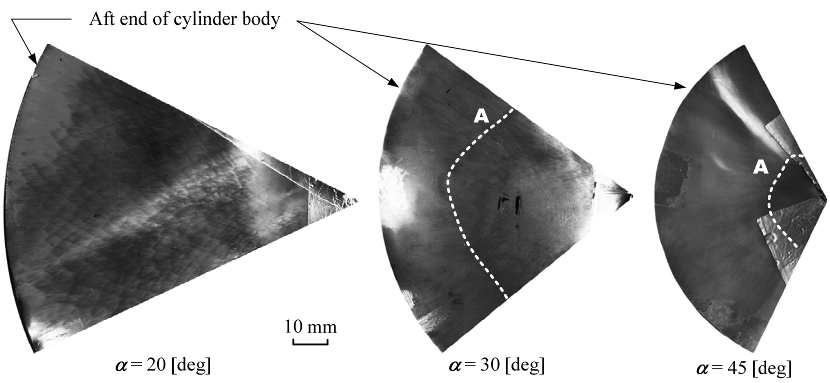

Figure 9. Soot tracks of the conical body sidewall for Ar = 75 %.

cylinder body, as shown in the 20° case, was observed only under conditions below 30°, and was never observed in cases with angles greater than 30°. This was because the transverse waves in a detonation wave could reach the sidewall of the expanding channel when the angle was sufficiently small and produced a strong reflection from the wall. These tendencies were quite similar to those under the nitrogen-dilution conditions.

4 Conclusion

The toroidal detonation wave propagation through a gradually expanding channel in argon-diluted stoichiometric H_2-O_2 mixtures has been investigated. Two different propagation modes, a continuous propagation mode and a temporal quenching mode, were observed. In the temporal quenching mode, the detonation wave was quenched by the expansion wave generated from the expanding channel exit. The boundaries of these two modes at each angle of the expanding channel were revealed by using the ratio of the annular gap width to the cell size of the detonation wave ($\boldsymbol{L/\lambda}$). When the angle was greater than 30°, the threshold value of $\boldsymbol{L/\lambda}$ was approximately 4, which was the same as the value at 90°. On the other hand, the promotion effect obtained by a conical body of 15° was extremely high, and the threshold value was approximately 2. This was because the transverse waves in a detonation wave could reach the sidewall of the expanding channel when the angle was sufficiently small and produced a strong reflection from the wall. These tendencies were quite similar to those under nitrogen-dilution conditions.

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