Planar toroidal detonation propagation through gradual expanding channel

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1 Introduction

A pulse detonation engine (PDE), in which propellant burns in detonation waves intermittently, has attracted the attention of researchers because of its simplicity and theoretical higher thermal efficiency [1-4]. The major issue that needs to be resolved for the practical use of a PDE is “detonation initiation.” Detonability is an indicator of the ease of initiating detonation of combustible mixtures. When a PDE operates in air-breathing mode, the combustible gas is likely to be a fuel-air mixture and its detonability—meaning detonation initiation ability of the combustible mixture—is lower than that of fuel-oxygen mixtures [5]. Another case in which one may encounter a low-detonability condition is when the fuel is in the liquid phase. The energy required to initiate detonation with low-detonability propellants such as those mentioned above is too large to directly initiate a detonation wave using a typical energy source [4].

To initiate a detonation wave using a typical energy source, many researchers employ a “predetonator." A detonation wave readily commences in a small diameter tube (predetonator) filled with a sensitive mixture (driver gas). In the next stage, the detonation wave transmits into a larger-diameter detonation chamber containing a low-detonability mixture of propellants (target gas) [4]. Detonation transition through an abrupt area change, such as from the predetonator to the main chamber, is foremost interest in the field of fundamental detonation study, and there have been many investigations concerning this issue [6-9]. Many researches have shown that the tube diameter $\boldsymbol{d}$ must be at least 13 times the cell size λ for a successful detonation transition [10-12]. Although many subsequent experimental studies showed that $\boldsymbol{d_c} = 13\lambda$ does not work out, which has been well reviewed in [13], this relational expression is effective in our experimental setup. Many methods to increase the detonation transmission efficiency at the abrupt change of area have been proposed. Typical methods are the use of : 1) shock reflection and shock-focusing devices [14-16], 2) a cone-shaped exit having a gradual area change to reduce lateral expansion [17-20].

To enhance the transmission efficiency of the predetonator, the authors have proposed a combination method of a "reflector" and "overfilling" of the driver gas [21, 22]. A detonation wave propagates around the reflector changing its shape through three transition processes: from planer to cylindrical, toroidal, and back to planar again. In this study, the authors have conducted experimental investigations with stoichiometric hydrogen/oxygen mixtures diluted with nitrogen to reveal effects of the annular gap width and the conical angle of the flow passage around the reflector on the transition from a toroidal wave to a planar wave.

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2 Experimental Set-up

Figure 1 shows a schematic of the experimental apparatus. It consists mainly of a detonation chamber and a predetonator. The detonation chamber is 280 mm long with an internal diameter of 100 mm. The predetonator upstream of the detonation chamber is 540 mm long with an internal diameter d of 10 mm. This length is sufficiently long compared with the DDT length of a stoichiometric hydrogen-oxygen mixture for this tube diameter. Four shafts support the reflector, which consists of a cylinder body and a conical body. The length of the cylinder body $\boldsymbol{l}$ is about 200 mm. The authors chose the reflector clearance $\boldsymbol{w}$, which is the distance from the predetonator exit to the upstream surface of the cylinder body, to be 10 mm. Soot foils collect tracks of the triple points of detonation waves at the following four locations in Fig. 1: I. the sidewall of detonation chamber, II. the sidewall of the cylinder body and III. the sidewall of the conical body.

The authors conducted a set of experiments to reveal the effect of the half angle of the conical body $\boldsymbol{\alpha}$ and the annular gap width $\boldsymbol{L}$ on the detonation transition from toroidal to planar. The gap $\boldsymbol{L}$ varied from 5 mm to 20 mm with steps of 5 mm. The half angle of the conical body $\boldsymbol{\alpha}$ varies from 15° to 90° with steps of 15°. The authors used an overfilling method to initiate a toroidal planar wave propagating the annular path filled with the target gas. To overfill the driver gas in the combustion chamber, an additional volume was installed in the upstream of the predetonator, as shown in Fig. 1. The additional volume is a 20 mm I.D. tube and is connected with the predetonator via a ball valve. Figure 2 shows the overfilling procedure. Initially, the valve is closed and the driver gas mixture and the target gas mixture fill the upstream and downstream areas of the valve, respectively (Fig. 2-(A)). A gas-handling machine prepares and completely mixes these mixtures. The pressure of the driver gas $\boldsymbol{p_1}$ is higher than that of the target gas $\boldsymbol{p_2}$. When the valve opens (Fig. 2-(B)), the driver gas overfills to the position $\boldsymbol{h}$ where the balance pressure $\boldsymbol{p_3}$ is established. Common to all experiments, the balance pressure (initial pressure) is 1 atm. A control device determines the timing of the valve opening and ignition, and activates a spark plug 1 sec after the valve opens. The authors chose the $\boldsymbol{h}$ to be 30 mm. Driver gas mixture is stoichiometric hydrogen-oxygen mixture, and target gas mixtures are stoichiometric hydrogen-oxygen mixtures diluted with nitrogen.

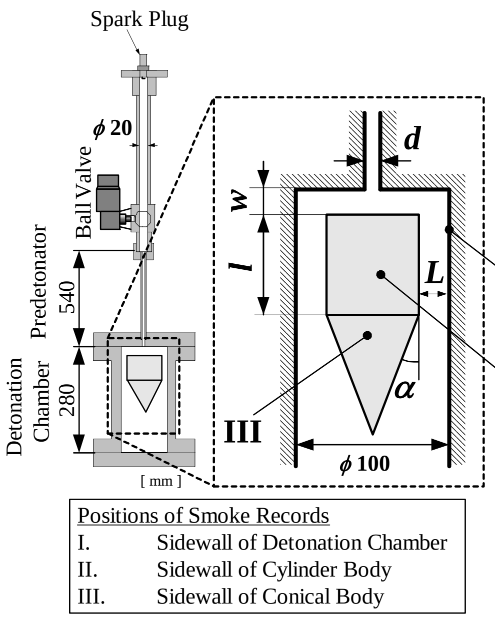

Figure 1. Experimental apparatus.

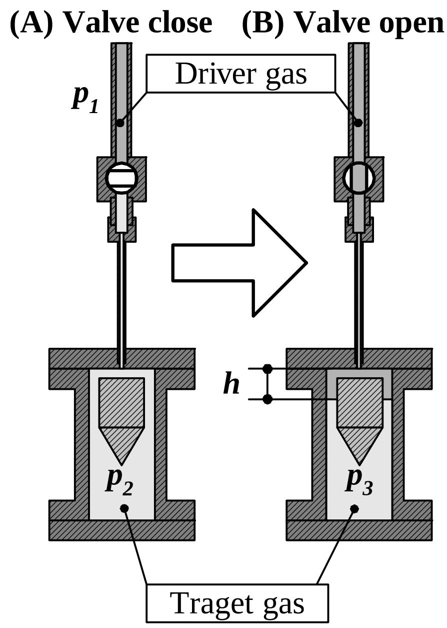

Figure 2. Overfilling procedure.

3 Results and Discussion

Figure 3 shows soot tracks of the detonation chamber with $\boldsymbol{L}$ = 10 mm and $\boldsymbol{\alpha}$ = 90°, meaning that the conical body is not used. The detonation wave travels from the left to the right. The broken line B shows the aft end of the cylinder body. The above track of Fig. 3 shows a “Go” case at $\mathbf{N_2}$ = 10%. Cellular structures covered entire section of the surface and any temporal quenching was not observed. In contrast, in the bottom track, the cellular structure disappeared from the line B at about 20 mm downstream. 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 is observed as "Nogo". Incidentally, even for a condition of "Nogo", re-initiation of the detonation wave was confirmed downstream of the detonation chamber like D in Fig. 3 for all of the conditions that we have conducted.

Figure 4 summarizes all of the experimental results showing the dependence of annular gap width to cell size ratio of detonation waves ($\boldsymbol{L}/\boldsymbol{\lambda}$) on Go/Nogo 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 (on the broken line A in Fig. 3). Open symbols represent cases of “Go” and solid symbols represent cases of “Nogo”. Note that plots for every half angle are staggered according to the gap width $\boldsymbol{L}$ ($\boldsymbol{L}$ = 5, 10, 15 and 20 mm from left to right) to avoid overlapping of plots. The threshold value of “Go” and “Nogo” is approximately 4 at $\boldsymbol{\alpha}$ = 90° that means there is no conical body. An earlier study revealed that when a detonation wave transits from a rectangular channel to an unconfined space, the critical value of $\boldsymbol{W}/\boldsymbol{\lambda}$ is 10. Here, $\boldsymbol{W}$ is the width of the flow path. Mitorofanov and Soloukhin showed that $\boldsymbol{W}/\boldsymbol{\lambda}$ decrease to an asymptotic value of 3 as aspect ratio of the channel (width/depth) goes to infinity [10, 18]. Comparing $\boldsymbol{L}/\boldsymbol{\lambda}$ with the half value of $\boldsymbol{W}/\boldsymbol{\lambda}$, the threshold value of 4 is acceptable. When the conical angle $\boldsymbol{\alpha}$ is 30°, 45° or 60°, almost the same threshold value of approximately 4 were observed. Accordingly, when the angle exceeds 30° degrees, the conical body has no effect on detonation transition enhancement. On the other hand, the promotion effect obtained by the conical body of 15° is extremely high and the threshold value decreases to approximately 2. There are many studies on transition of detonation waves passing through a convex corner with rectangular or circular section [12,19]. In a rectangular section, Thomas et al. showed that the critical ratio of the channel width to the cell size increases up to 55° of the corner angle and remains constant to 90° [18]. In circular section, Khasainov et al. showed the threshold angle is about 40° [20]. So, a qualitative tendency of our research coincides with the past researches.

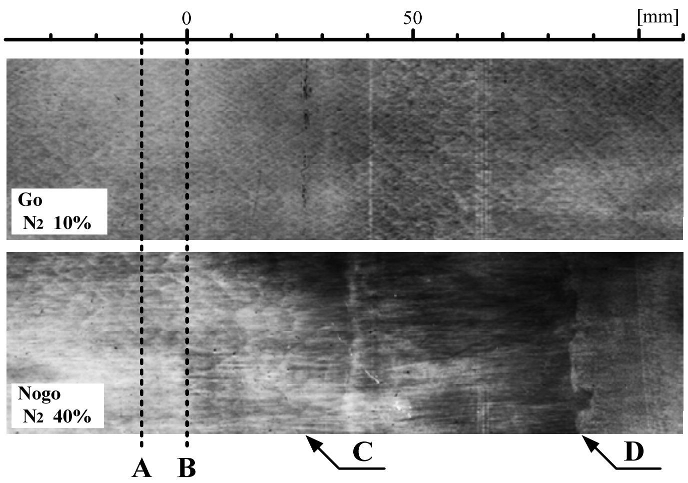

Figure 3. Soot tracks of the detonation chamber sidewall at $\boldsymbol{L}$ = 10 mm and $\boldsymbol{\alpha}$ = 90°.

Figure 5 shows the soot tracks on the detonation chamber, the cylinder body, and the conical body with $\boldsymbol{L}$ = 15 mm, α = 90° and $\mathbf{N_2}$ = 40 %. Cellular structures cover entire section of the tracks. Note that the cellular structures continue without a break over the cylinder body and the conical body. This continuous cellular transition was observed in all of the "Go" conditions for α = 15°. In contrast, this continuous cellular structure was never observed at any other conditions except these conditions. Figure 6 shows a 2D conceptual diagram of the transition of the planar toroidal detonation at the convex corner. As discussed briefly, a detonation wave consists of the three shocks: the incident shock, the Mach stem and the transverse shock. The interactions of the transverse shock with each other or with the wall produce a local explosion. The heavy broken line **A** in Fig. 6 shows the head of the transverse shock (the same as the trajectory of the triple point), 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, for example 15° wall in Fig. 5. Accordingly, the reflection of the transverse shock on the upstream of the conical body plays an important role in promoting the detonation transition when the conical angle is small.

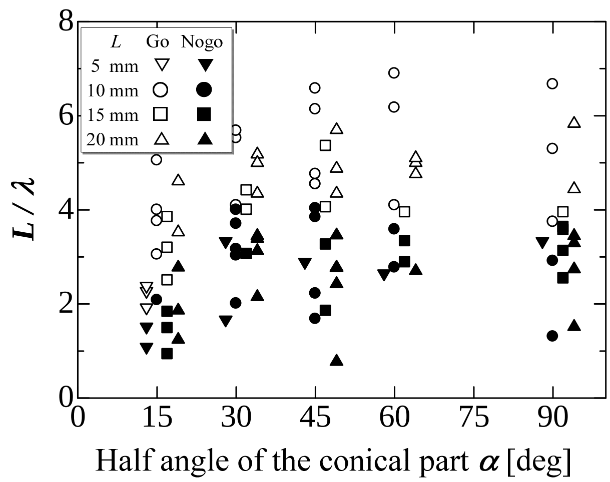

Figure 4. The transition status

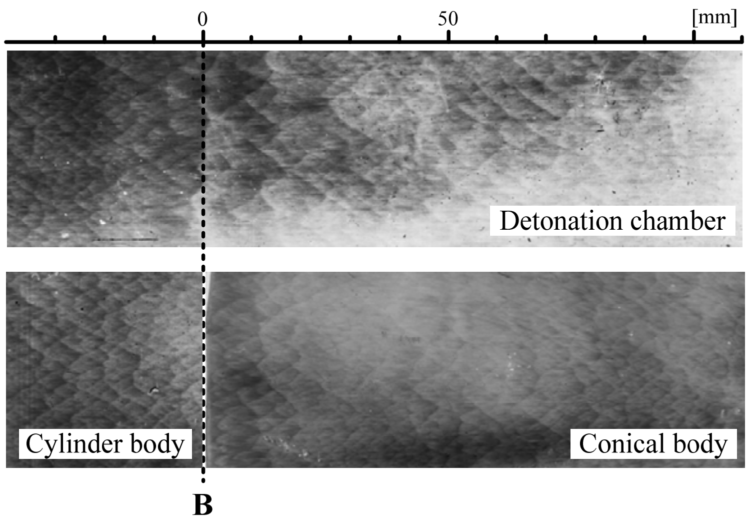

Figure 5. Soot tracks of the detonation chamber, the cylinder body and the conical body at L = 15 mm, α = 90° and N_2 = 40 %.

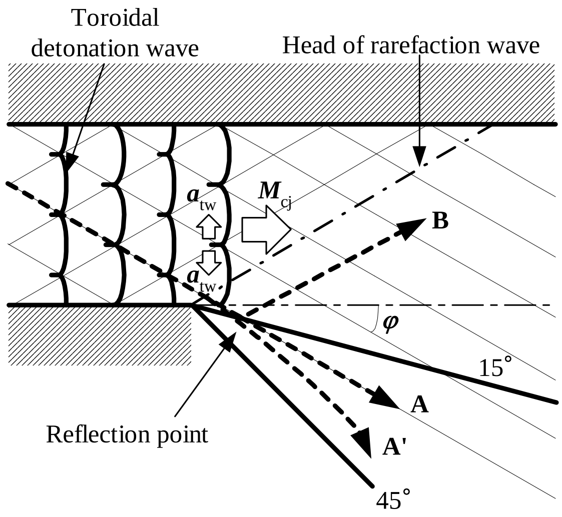

Figure 6. 2D conceptual diagram of the transition of the planar toroidal detonation at the convex corner.

4 Conclusions

Experimental investigations of the toroidal planar detonation wave propagation around the reflector, which consists of a cylinder body and a conical body, revealed the effects of the ratio of the annular gap width and cell size of the detonation wave (L/λ) on the detonation transition. When the conical angle α is 30°, 45° or 60°, the threshold value of L/λ between the "Go" and "Nogo" is approximately 4, which is the same as the value at α = 90°. Accordingly, when the angle exceeds 30°, the conical body has no effect on detonation transition enhancement. On the other hand, the promotion effect obtained by the conical body of 15° is extremely high and the threshold value is approximately 2. This is because transverse waves in a detonation wave can reach the sidewall of the conical body, when the conical angle is sufficiently small, and it produces a strong reflection on the wall.

Acknowledgments

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