Influence of Channel Width on Cylindrical Detonation Wave Propagation

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To achieve stable detonation wave propagation to large-bore pulse detonation engine (PDE) combustors, we investigated an initiator for PDEs that uses a pre-detonator, reflector, and driver gas. In this initiator, a planar detonation wave from the pre-detonator becomes a cylindrical detonation wave after collision with the reflector. Wakita et al. previously posited two hypotheses regarding the dominant factors that determine the threshold of propagation to the target gas, which is a stoichiometric hydrogen–oxygen mixture diluted with nitrogen. This study reveals whether the threshold is determined by \( w/\lambda \) or \( \lambda/r \). To analyze the effect of channel width \( w \) on the transition of the cylindrical detonation wave, experiments were conducted for \( w = 10 \) mm and \( w = 15 \) mm. However, the results could not elucidate whether the threshold is determined by \( \lambda/r \) or \( w/\lambda \). To clearly distinguish between the effects of \( w/\lambda \) and \( \lambda/r \), a narrow channel width \( w' = 3 \) mm was chosen and implemented using a torus-shaped obstacle. The results showed that a cylindrical detonation wave propagates without quenching when the nitrogen concentration is above 40%, corresponding to the cell size \( \lambda \) greater than \( w \). Accordingly, the cylindrical detonation propagation threshold was determined to be independent of \( w/\lambda \).

Key Words: Detonation Initiation, Pulse Detonation Engine

Nomenclature

- \( w \): channel width
- \( w' \): channel width of torus-shaped obstacle
- \( \lambda \): cell size
- \( R \): overfilling radius
- \( r \): curvature of detonation wave

1. Introduction

Pulse detonation engines (PDEs), in which intermittent detonation waves burn the propellant, have attracted much attention because of their simplicity and high theoretical thermal efficiency.1-4) However, to enable the practical use of PDEs, the major issue of “detonation initiation” must be resolved. In the air-breathing mode, the combustible gas is likely to be a fuel–air mixture, and the sensitivity of the combustible mixture is lower than that of fuel–oxygen mixtures.5) The sensitivity may also be low when the fuel is in the liquid phase. In these low-sensitivity cases, the initiation energy required for direct initiation is so large that the deflagration-to-detonation-transition (DDT) process is commonly used in PDEs.5) Generally, large-bore combustors and low-detonability mixtures tend to require longer DDT distances, resulting in lower operating frequencies and thermal efficiencies. Thus, a detonation initiation method must be developed for high-thrust large-bore combustors that can be used with a real space plane.

Another possible method of detonation initiation uses a “pre-detonator,” as shown in Fig. 1(a). In this method, a detonation wave is readily initiated in a small diameter tube (pre-detonator) filled with a sensitive mixture (driver gas). In the next stage, the detonation wave is transmitted to a larger diameter detonation chamber containing a mixture of propellants (target gas) with low sensitivity.5) Detonation transition through an abrupt area change, such as from the pre-detonator to the main chamber, is of foremost interest in the field of fundamental detonation study, and there have been many investigations concerning this issue.6-9) Many studies have shown that the tube diameter \( d \) must be at least 13 times the cell size \( \lambda \) for successful detonation transition.10-12) Although many subsequent experimental studies, particularly reference 13) has shown that \( d_c = 13 \lambda \) is not always suitable, this relational expression is effective in our experimental setup. Furthermore, many methods for increasing the detonation transmission efficiency at the abrupt area change have been proposed. Typical methods involve the use of shock-reflection and shock-focusing devices,14-16) or a cone-shaped exit with a gradual area change that reduces lateral expansion.17-20)

To enhance the transmission efficiency of the pre-detonator, a combination method using a “reflector” and “overfilling” of the driver gas was proposed in references 21) and 22), as shown in Fig. 1(b). Figure 2 shows a schematic diagram of a large-bore PDE, which will be examined in a future study. The detonation wave propagates around the reflector, changing its shape through three transition processes: from planer detonation wave \( A \) to expanding cylindrical detonation wave \( B \), then to imploding toroidal detonation wave \( C \), and back to planar detonation wave \( D \). The authors showed that successful detonation propagation in a 100 mm diameter
The combustor is realized in the cases that the transition process from the incident planar detonation wave $A$ to the expanding cylindrical detonation wave $B$ is realized. In the 100 mm diameter combustor, to make the first transition process successful by using the overfilling of the driver gas (stoichiometric hydrogen–oxygen mixture), as shown in Fig. 1(b), the target gas (stoichiometric hydrogen–air mixture) upstream of the reflector must be completely replaced by the driver gas mixture.\footnote{22}

It is suggested that the larger the detonation curvature, $\lambda/r$, the more difficult the propagation of cylindrical detonation. Therefore, cylindrical detonation waves once initiated propagate stably. To generate cylindrical detonation waves that propagate to a large diameter detonation combustor (Fig. 1(c)), the driver gas is filled on the inner side of $R$ without mixing with the target gas. The necessary filling diameter $R$ of the driver gas (stoichiometric hydrogen–oxygen mixture) to propagate the cylindrical detonation waves to the target gas (stoichiometric hydrogen–air mixture) by using a 500 mm diameter cylindrical combustor has been investigated earlier.\footnote{23} It was confirmed that $R = 100$ mm is the threshold condition. Figure 3 indicates that this threshold has two factors. First, if $R$ is small enough, about 75 mm, cylindrical detonation waves cannot propagate to the target gas, mainly because their large curvature makes it difficult to propagate. Second, if the dilution ratio of the target gas is large enough, about 55.6%, cylindrical detonation waves cannot propagate to the target gas. The dilution ratio threshold is valid if $R$ is large enough. Wakita et al.\footnote{23} assumed two hypotheses for the dominant factors determining the second threshold. One is the ratio of cell size to the curvature of cylindrical detonation waves, $\lambda/r$. They supposed the curvature of cylindrical detonation waves at the boundary of the driver and target gases as well as the ratio of channel width to the cell size $w/\lambda$ determine the threshold. The 500 mm diameter combustor’s channel width is 10 mm and the threshold condition is $w/\lambda = 1$. Therefore, it is also supposed that cylindrical detonation waves cannot propagate in the channel whose width is smaller than their cell sizes because the narrow channel obstructs the cell structure.

In this paper, the authors determine whether the second threshold depends on $\lambda/r$ or $w/\lambda$. To this end, the authors investigated the influence of channel width $w$ and nitrogen concentration of the target gas on cylindrical detonation wave propagation. However, it is well known that the ratio of the pre-detonator diameter to the channel width affects the initiation of cylindrical detonation waves. Therefore, in this experiment, the channel width was changed after cylindrical detonation waves were initiated.

2. Experimental Details

The schematic diagram of the combustion chamber is shown in Fig. 4. It mainly consists of a cylindrical detonation chamber and a pre-detonator; the cylindrical detonation chamber has two stainless steel flanges separated by a spacer. Two values of spacer thickness $w$ were used: $w = 10$ mm and $w = 15$ mm. The detonation chamber diameter is 500 mm and the total length of the pre-detonator, which is vertically connected to the upper flange of the chamber, is 1066 mm. Therefore, the planar detonation wave, initiated by the pre-detonator, would be diffracted by 90° at the pre-detonator exit and converted to a cylindrical detonation wave. The pre-detonator is constructed in three sections. The first section, which forms the top of the pre-detonator, is 280 mm in length with a 10.7 mm inner diameter; it is installed with a spark plug...
for ignition. The second section is 750 mm in length with a diameter of 20.4 mm. The third section is the connecting section with a diameter of 20 mm and a length of 36 mm. The total length of the pre-detonator is sufficient compared with the DDT length of the stoichiometric hydrogen–oxygen mixture (driver gas mixture) required for this tube diameter.

To overfill the driver gas in the cylindrical detonation chamber, the pre-detonator is divided by a ball valve 446 mm upward from the upper flange of the chamber. This ball valve enables separately filling gases of different compositions in the upstream and downstream areas.

Figure 5 illustrates the overfilling procedure. Initially, the ball valve is closed (left side of Fig. 5), and the driver gas mixture and target gas mixture fill the areas upstream and downstream of the valve, respectively. The pressure of the driver gas $P_1$ is higher than that of the target gas $P_2$. When the valve opens (right side of Fig. 5), the driver gas expands to the position $R$ to establish the balance pressure $P_3$. In all experiments, the balance pressure was 1 atm. The driver gas used in the experiments was a stoichiometric hydrogen–oxygen mixture, whereas the target gas was a stoichiometric hydrogen–oxygen mixture diluted with nitrogen. The filling pressure before opening of the ball valve for various overfilling conditions is shown in Table 1. The mixtures were ignited by the spark plug 1 s after the opening of the ball valve.

The detonation cell structure was visualized using a soot foil placed at the surfaces of the lower flange of the cylindrical detonation chamber. The thickness of the soot film was 0.1 mm, and a stainless steel plate with dimensions 300 mm × 400 mm was used. The experimental apparatus had seven pressure sensor ports (PCB 113A26 or 113B26, Piezotronics Co., Ltd.), and the detonation propagation velocity was calculated from the time difference of pressure increases between the P1 and P2 ports and that between the M1 and M4 ports in experiments of $w = 10$ mm, or from the time difference of pressure increases between the P2 and M1 ports and that between the M4 and M5 ports in experiments of $w = 15$ mm. The detonation propagation velocity was validated by comparison with the theoretical speed determined by the initial state and gas compositions.

3. Results and Discussion

3.1. Influence of channel widths $w$ of 10 mm and 15 mm

The success (Go) and failure (No Go) of the detonation transition is determined by whether the cell patterns are confirmed 200 mm downstream of the chamber center, as shown in Fig. 6. Figures 7 and 8 show the Go/No Go maps of the detonation transition with channel widths of 10 mm and 15 mm, respectively. The vertical and horizontal axes denote the nitrogen concentration and overfilling radius of the driver gas mixture, respectively. These experimental results show that the border between the Go and No Go maps consists of two straight lines; one is a transverse line (broken line) and the other is a horizontal line (solid line). When the overfilling radius is lesser than 100 mm, the nitrogen concentration threshold of the target gas increases with the overfilling radius. On the other hand, when the overfilling radius is greater than 100 mm, the nitrogen concentration threshold of the target gas is constantly between 50% and 55.6% for both channel widths. When the overfilling radius is greater than 100 mm and the nitrogen concentration threshold of the target gas is less than 55.6%, the cylindrical detonation wave can propagate from the driver gas section to the target gas region. To evaluate the effect of the number of cells on the channel width, the Go/No Go maps were reevaluated with $w/\lambda$, as shown in Figs. 9 and 10, where $w$ and $\lambda$ are the channel width (10 mm or 15 mm) and the cell size of the cylindrical detonation wave in the target gas mixture, respectively. In this experiment, the cell size was calculated using the fitted curve in Fig. 11 when...
the detonation transition was successful. In reference 24), this approximation formula was derived from the average cell size measured three to ten times under the same conditions. The vertical and horizontal axes represent $w/\lambda$ and the overfilling radius of the driver gas mixture, respectively. Figures 9 and 10 show that the boundary values of $w/\lambda$ in both dilution cases are about 1.5 when the overfilling radius is greater than 100 mm, which is sufficient to obtain a stable cylindrical detonation wave. However, these results could not elucidate whether the threshold is determined by $\lambda/r$ or $w/\lambda$, because $\lambda$ increases rapidly with the nitrogen concentration of the target gas when the concentration is greater than 50%, as shown in Fig. 11. To clarify the influence of the ratio between the channel width and the cell size on the Go/No Go maps of the transition, experiments must be performed in a low nitrogen concentration region, in which the cell size does not change rapidly with increase in the nitrogen concentration.

3.2. Influence of channel width $w = 3$ mm

To investigate whether the cylindrical detonation propagation threshold is determined by $\lambda$ or $w/\lambda$, the cell size of the target gas must be accurately adjusted. Accordingly, experiments in a region with smaller $\lambda$ are preferable. To this
end, a narrow channel width \( (w' = 3 \text{ mm}) \) was chosen. To establish a stable cylindrical detonation wave in this condition, we employed a torus-shaped obstacle with a 300 mm inner diameter, as shown in Figs. 12–14. This shape is necessary because the channel width \( w' = 3 \text{ mm} \) is too small for a successful transition from a planar to cylindrical detonation wave.\(^{21}\) The stable cylindrical detonation wave generated in the area with \( w = 10 \text{ mm} \) entered into the area with \( w' = 3 \text{ mm} \). Its behavior was observed by the soot foil method. To measure the detonation speed in the narrow channel region, P1, P2, M4, and M5 pressure ports were used. In both regions, the soot tracks were obtained on the lower surface of the combustion chamber. The overfilling radius \( R \) was 100 mm, which is sufficient to generate a stable cylindrical detonation wave.

The success (Go) and failure (No Go) of the detonation propagation is determined by whether cell patterns are confirmed in the narrow width region, as shown in Fig. 15. Figure 16 shows the Go/No Go maps; symbols of plus and
cross represent Go and No Go, respectively. The vertical and horizontal axes denote the nitrogen concentration and channel width, respectively. These experiments were conducted more than two times under the same conditions, and the same results were obtained. The threshold of nitrogen concentration for a successful detonation propagation is near 55.6%, which is consistent with the previous result for an overfilling radius greater than 100 mm (see Figs. 7 and 8). Figure 17 shows the relationship between $w/\lambda$ and $R$. It can be clearly observed that $w/\lambda$ changes with the channel width. Accordingly, the nitrogen concentration threshold for successful detonation propagation is not determined by $w/\lambda$.

4. Conclusion

This study revealed the characteristics of cylindrical detonation propagation by using two channel widths ($w = 10$ mm and $w = 15$ mm) to investigate its dependency on $\lambda/r$ and $w/\lambda$. The experiments showed that the nitrogen concentration threshold for successful detonation propagation is near 55.6% for both channel widths, and the results for $w/\lambda$ showed almost no variation. Furthermore, a torus-shaped obstacle was employed to create a narrow channel in the combustion chamber. This obstacle enabled investigating the threshold under the conditions of low dependency of cell size on nitrogen concentration. The results confirmed the propagation to the target gas under the condition of nitrogen concentration greater than 40% when $w/\lambda$ was smaller than one. On the other hand, the nitrogen concentration threshold of the target gas was between 50% and 55.6%, which is consistent with the experimental results for the other channel widths. Therefore, the nitrogen concentration threshold of cylindrical detonation wave propagation is independent of $w/\lambda$ when stable cylindrical detonation waves are generated.

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References