Development of Pulse Detonation Engine Initiator
Using Reflector for Large Bore Combustor

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To achieve reliable transmission of detonation wave to a pulse detonation engine (PDE) combustor, authors have proposed a PDE initiator, which consists of a predetonator and a reflector. A detonation wave propagates around the reflector changing its shape through three transition processes; from planer to cylindrical, toroidal, and planar again. Our previous study revealed that the transition to the cylindrical detonation wave upstream of the board plays a significant role in detonating hydrogen-air mixture in a 100-mm-diam-combustor. A self-sustainable condition of the cylindrical detonation wave is severe when the radius of the wave front is small. In cases using hydrogen-oxygen mixture as driver gas for the 100-mm-diam-combustor, we had to fulfill with driver gas entire upstream of the board at the critical condition for the transition to the cylindrical wave. On the other hand, curvature of the cylindrical detonation wave front becomes smaller with increasing radius of the front, so the self-sustainable condition of the cylindrical wave must be mitigated for a large bore combustor. In this study, we investigated the necessary filling diameter of the driver gas to detonate hydrogen-air cylindrical detonation by using a 500-mm-diam-cylindrical-combustor.

Key Words: Pulse Detonation Engine, PDE Initiator, Cylindrical Detonation Wave, Detonation Transition

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.” Detonation is an indicator of the ease of initiating detonation chamber containing a low-detonability mixture of propellants (target gas) $^{5}$. 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 $d$ must be at least 13 times the cell size $\lambda$ for a successful detonation transition $^{10-12}$. Although many subsequent experimental studies showed that $d_c = 13\lambda$ does not work out, which has been well reviewed in Ref. 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 $^{14-16}$, (b) 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, as shown in Fig.1-(b) $^{21, 22}$. A detonation wave propagates around the reflector changing its shape through three transition processes: from planer detonation wave to expanding cylindrical detonation wave, imploding toroidal detonation wave, and back to planar detonation wave again, as shown in Fig. 2. The authors revealed that the transition from the incident planar detonation wave to an expanding cylindrical detonation wave in the first transition process is a sufficient condition for
successful detonation wave propagation in the detonation chamber [21]. To make the first transition process successful by using the "overfilling" of the driver gas, as shown in Fig.1-(b), the target gas mixture upstream of the reflector must be completely replaced by the driver gas mixture [22]. In other words, the expanding cylindrical detonation wave fails if the driver gas is not filled up to a full radius for a small bore combustor. In this case, the combustor radius was 50 mm. On the other hand, the self-sustainable condition of the expanding cylindrical detonation wave must be mitigated for a large bore combustor, and the wave may not fail even if the driver gas is not filled up to a full radius, because the area change rate or the curvature of the cylindrical detonation wave front becomes smaller with increasing radius of the front, as shown in Fig.1-(c). In this study, we investigated the necessary filling diameter of the driver gas to detonate hydrogen-air cylindrical detonation by using a 500-mm-diam-cylindrical-combustor.

2. Experimental Details

Figure 3 and figure 4 show a schematic and cover shot of the experimental apparatus, respectively. It mainly consisted of a cylindrical detonation chamber and a predetonator. The chamber consisted of two stainless-steel flanges which separated by a spacer of 10 mm in thickness. The chamber diameter was 500 mm. The predetonator 629 mm long with an internal diameter of 10.7 mm was vertically connected with the upper flange of the chamber, so that the planar detonation wave in the predetonator would be diffracted by 90° at the exit and change to the cylindrical wave. This length of the
predetonator is sufficiently long compared with the DDT length of stoichiometric hydrogen-oxygen mixture (driver gas mixture) for this tube diameter. This apparatus has seven ports from PS1 to PS7 for pressure sensors (PCB 113A26 or 113B26, Piezotronics Co., Ltd.). The pressure history was acquired in four arbitrary ports a condition at the same time. Detonation cell structure was collected by a soot foil at a surface of the lower flange of the cylindrical detonation chamber.

To overfill the driver gas in the cylindrical detonation chamber, an additional volume tube 730 mm long with an internal diameter of 20.4 mm was connected with the predetonator and the predetonator was divided by a ball valve oriented at 229 mm upstream from the exit, as Fig. 3 shows. Figure 5 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. 5(A)). A gas-handling machine prepares and completely mixes these mixtures. The pressure of the driver gas \( p_1 \) is higher than that of the target gas \( p_2 \). When the valve opens (Fig. 5-(B)), the driver gas overfills to the position \( R \) where the balance pressure \( p_3 \) is established.

Common to all experiments, the balance pressure (initial pressure) was 1 atm. In all cases, the driver gas and the target gas are stoichiometric hydrogen-oxygen and stoichiometric hydrogen-air mixtures, respectively.

Our previous research revealed that the successful transition from the incident planar detonation wave (Fig. 2-A) to an expanding cylindrical detonation wave (Fig. 2-B) occurs when the predetonator diameter \( d \) is larger than 6.3\( \lambda \), and the separation of the cylindrical chamber \( w \), or the spacer thickness, equals about 0.9\( d \). The cell size \( \lambda \) of a stoichiometric hydrogen-oxygen driver mixture is about 1.2 to 1.3 mm at 1 atm. Therefore, we chose the predetonator diameter \( d \) and the clearance between the flanges of the detonation chamber \( w \) to be 10.7 mm and 10 mm.

3. Results and Discussion

Filling the driver gas mixture (stoichiometric hydrogen-oxygen mixture) into the entire test section, we checked the detonation transition from driver gas mixture to driver gas mixture (driver-to-driver). The experimental procedure is the same as the overfilling procedure described in Fig. 5. Fig. 6 shows pressure histories at PS2, PS3, PS4 and PS5 with an overfilling radius \( R \) of 150 mm. The \( p_1 \), \( p_2 \), and \( p_3 \) were 3 atm, 0.6 atm and 1 atm, respectively. All of the pressure histories exhibit a rapid pressure rise. The time lags of the steep pressure rises of PS2-PS3, PS3-PS4 and PS4-PS5 were 135 \( \mu s \), \( 14.1 \mu s \) and \( 15.1 \mu s \), respectively. The distance between PS2 and PS3 equals 371 mm including the clearance between the flanges, and each distance between main ports (PS3-PS4, PS4-PS5) was 42 mm. From these relations, the velocities of the combustion wave between these ports were 2.75 km/s, 2.98 km/s and 2.78 km/s. The velocities of PS2-PS3 and PS4-PS5 were close to the theoretical Chapman-Jouguet (CJ) detonation velocity of 2.8 km/s under a stoichiometric hydrogen-oxygen mixture. Accordingly, a CJ detonation wave is transmitted along the axis in the predetonator and the...
combustion chamber. The velocity of PS3-PS4 was slightly higher than the CJ value. Fig. 7 shows a soot track at the surface of the lower flange of the cylindrical detonation chamber in the same condition. This is a tone invert image for clear vision. The planar detonation wave emerging from the predetonator has attenuated completely by the expansion wave.
before reaching a lower flange surface. However, the attenuated wave collides with the wall surface and the local explosion was occurred at the center black area of the soot foil. The radial detonation wave, which has very fine cellular structure, was observed from the outer edge of the black area. The cellular structure grows with increase in radius and collapses between 20 mm and 30 mm in radius once. The stable expanding detonation wave eventually re-initiate on the circumference of about 30 mm in the diameter. It would appear that the velocity of PS3-PS4 was slightly higher than the CJ value because the state immediately after the re-initiation of the detonation wave is overdrive.

By using the target gas mixture (stoichiometric hydrogen-Air), we examined the detonation transitions from driver-to-target by changing the overfilling radius \( R \). Fig. 8-a) shows soot track and pressure history with overfilling \( R \) of 50 mm. The \( p_1 \), \( p_2 \) and \( p_3 \) for the \( R \) of 50 mm were 1.2 atm, 0.95 atm and 1 atm, respectively. The pressure history shows that the combustion wave velocities of PS2-PS3, PS3-PS4 and PS4-PS5 were 2.50 km/s, 0.78 km/s and 0.70 km/s, respectively. The wave velocity of PS2-PS3 was slightly lower than the CJ value of driver gas mixture, and the others were very low. As shown in the soot track, as well as the driver-to-driver case, the radial detonation wave, which has very fine cellular structure, was observed at the central region. The cellular structure collapses in radius of around 15 mm. From these results, it is believed that the detonation wave, the velocity of which was CJ speed of driver gas mixture, propagated to the position of 15 mm in the radius, and after that it attenuated to the combustion wave, velocity of which was 800m/s. We had never observed the re-initiation of the detonation wave on the outside of the 15 mm, in all cases of 50 mm overfilling.

In the experimental results with overfilling \( R \) of 100 mm, the transition success case and the failure case were observed. The Fig. 8-b) shows the transition success case, and the failure case is similar to Fig. 8-a). The pressure history of Fig. 8-b) shows that the combustion wave velocity of PS3-PS4 was 2.64 km/s, which is lower than the CJ value of driver gas mixture and higher than the value of target gas mixture. From the soot track, we can confirm that the detonation wave re-initiated between 30 mm in the radius and 60 mm. Therefore, in this condition, the expanding cylindrical detonation wave might be re-initiated in the driver gas mixture first and spread to the target gas mixture afterwards. It is thought that the re-initiation of the detonation wave in the radius of 30 mm controls the transition success of the expanding detonation wave.

Figure 8-c) shows the soot track and pressure history with overfilling \( R \) of 150 mm. The \( p_1 \), \( p_2 \) and \( p_3 \) were 3 atm, 0.6 atm and 1 atm, respectively. The pressure history shows that the combustion wave velocities of PS2-PS3, PS3-PS4 and PS4-PS5 were 2.67 km/s, 2.41 km/s and 2.41 km/s, respectively. The velocity of PS2-PS3 was lower than the CJ value because the detonation wave has quenched on the inside of the PS3, like the other cases. The velocities of PS3-PS4 and PS4-PS5 were lower than the CJ value because of the mixing effect of the driver gas mixture and target gas mixture. As well as Fig. 8-b), we can also confirm that the detonation wave re-initiated between 30 mm in the radius and 60 mm. Note that the most inside re-initiation positions of the stable expanding detonation wave in Fig. 8-c), which is 30 mm in radius, is almost same as those in Fig. 7 and Fig. 8-b).

Figure 9 shows the soot track of the front flange surface in Reference 22, in which 100-mm-diam-combustor was employed. The front flange corresponds to the upper detonation chamber in this paper. The clearance between the flanges of the detonation chamber was also same as 10 mm. The detonable mixture was stoichiometric hydrogen-oxygen mixture. The left figure, the central white circle is the predetonator exit. An annular black ring surrounds the predetonator exit. The detonation cellular structure extends outside the black ring, which has 15 mm radius, as the close-up in the right figure shows.

Based on the soot tracks described in Fig. 8 and Fig. 9, we show a conceptual diagram of detonation transition from the planar detonation wave to the expanding cylindrical detonation wave. As well as Fig. 10-I) diffracts at the exit of the predetonator and is weakened by the expansion wave from the edge of the predetonator. At the center of the lower detonation chamber (Fig. 10-O) the detonation wave (Fig. 10-II) recommences and spreads to two areas, one is pink region and the other is yellow. The yellow region is pre-compressed area by the diffracted wave.
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Shock and the super detonation wave might pass through the region. In the pink region, the expanding cylindrical detonation wave spreads temporarily. However, the wave quenches at the point B. The radius of point B is about 20 mm. Meanwhile, the super detonation wave collides with the upper chamber wall at point A and initiate new strong expanding detonation wave (Fig. 10-II). The radius of point A is about 15 mm. The initiated detonation wave might pass through the pre-compressed area, which is made by preceding shock wave from the quenched detonation wave. In a word, an incident planar detonation wave changes to a steady expanding cylindrical detonation wave after repeating the strong reflection three times at point O, A and C. From these results, it seems that the initiation of the detonation wave between the point A and C plays an important role in transition to the stable expanding cylindrical detonation wave. To initiate the detonation wave, we might have to fulfill the driver gas mixture to the point C without mixing. It is thought that the overfilling distance \( R \) is necessary by more than 100 mm to fulfill the driver gas mixture to the point C.

4. Conclusions
In this study, we investigated the necessary filling diameter of the driver gas mixture (stoichiometric hydrogen-oxygen) to detonate hydrogen-air cylindrical detonation by using a 500-mm-diam-cylindrical-combustor. We confined that the strong reflections of the detonation wave occurred at the combustor wall surface three times when the incident planar detonation wave successfully changes to a steady expanding cylindrical detonation wave. Especially, the reflection of the detonation wave in the second reflection plays an important role in transition to the stable expanding cylindrical detonation wave. The necessary overfilling distance of the driver gas mixture is more than 100 mm to initiate the detonation wave in the second reflection.

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