# Experimental Investigation for Delay Time Phenomenon in Continuous Detonation Engine

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## 1    Background

Based on nearly isochoric combustion process, the detonation engine, especially the continuous detonation engine (CDE), inherently enjoys higher thermodynamic efficiency and specific impulse. Taking advantage of self-compressing and continuous rotating detonation wave (CRDW), the CDE is capable to run with a simple and compact structure. It is expected to break the bottleneck encountered by conventional deflagrations-based propulsion devices. The basic concept of CDE was first proposed by Voitsekhoviskii[1]. In the recent years, the CDE has been extensively studied both theoretically and experimentally due to its bright future. As for the injection patterns, Liu et al.[2] improved the numerical simulations of the CDE by discussing four new injection patterns, i.e. the mid-clit injection, the side-slit injection, the radial strip injection and the oblique strip injection. They found that the injection patterns affected the formation and stability of detonation wave. Yao et al.[3] studied a more practical injection pattern, injection via an array of holes, and captured a phenomenon observed in experiments but absent in previous numerical simulations. In their numerical simulation, there was an obvious delay time between the initiation and the start of the CRDW observed from the pressure histories. Wanlanski et al.[4] also found the delay period from the moment of initiation in the main chamber by a strong shock wave to the start of the rotation detonation in experiments. Yang et al.[5] conducted experimental research on the CDE and analyzed the initiation process of detonation wave with different ignition energy. They found that the formation time of detonation wave decreased significantly with a higher ignition energy. To shorten the delay time is of great importance to maintain the successive propagation of CRDW.

To better understand the formation of CRDW and delay time, series of experiments were carried out, which will be presented in this paper. The initiation characteristics of the CRDW are recorded and analyzed by a high frequency pressure measurement system.

## 2    Experimental Setup and Methodology

The entire experimental setup is shown in Fig. 1, including gas supplying system, combustion chamber, igniting system, exhausting system and data collecting system [6].
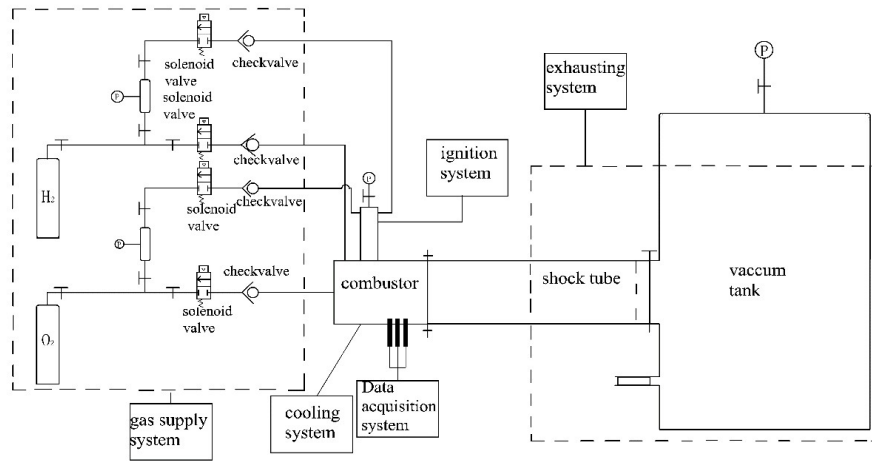
Figure 1 Experimental setup

The annular combustion chamber of CDE is shown in Fig. 2. The outer diameter, inner diameter and length of the chamber are 78mm, 58 mm and 150 mm respectively. The schematic of the injection pattern used in the present experiments is illustrated in Fig. 3. Non-premixed fuel and oxidizer are fed into the combustor through an array of holes at the head end. The injection via an array of holes for CDE was first proposed by Wang and its feasibility was demonstrated by Yao et al.[3]. The injection pattern can increase the injection area and minimize the loss of mixtures' momentum in the injection process. As the detonation wave propagates circumferentially in annular at the head, the burnt products are emitted through the exit.
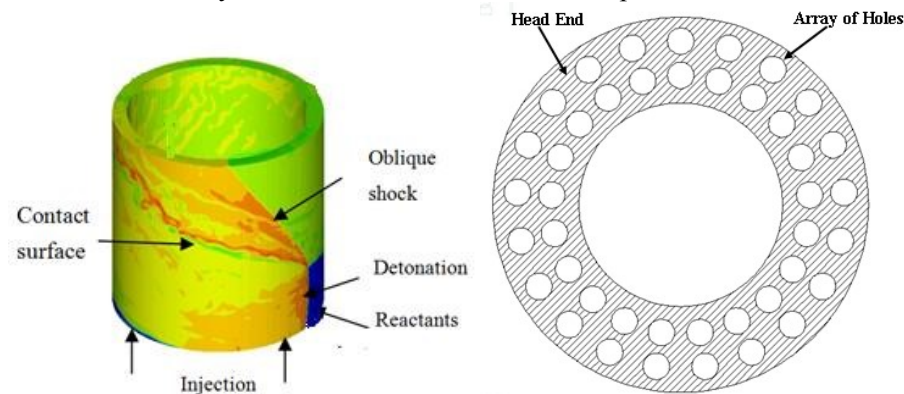


Figure 2 Annular combustion chamber of CDE    Figure 3 Schematic of the injection pattern

The gas mixture in the main combustor is ignited by a pre-detonator connected to the combustor cylinder tangentially. The pre-detonator is also filled with hydrogen and oxygen, and a spark plug ignites the detonable gas at the end. Deflagration to detonation transition completes within the pre-detonator with the help of Shchelkin spiral. The pre-detonator only needs to work at the beginning.

Gas feeding is controlled by an electromagnet-valve on each single pipeline. A computer program controls the electromagnet-valves and the spark plug separately. The experiments are conducted according to a specific time sequence as shown in Fig. 4. First, the pre-detonator $O_2$ and $H_2$ are opened. After a time interval $\Delta t_{p1}$, the main combustor $O_2$ and $H_2$ are opened. Meanwhile, the pre-detonator $O_2$ and $H_2$ are stilled supplied. After a time interval $\Delta t_{p2} = \Delta t_{m1}$, the pre-detonator is ignited by a spark plug. After the

pre-detonator is ignited, the pre-detonator $O_2$ and $H_2$ can be stilled opened for a time interval of $\Delta t_{p3}$. Time interval $\Delta t_{m2}$ is working time. The combination of time intervals should be precisely set. If $\Delta t_{p1}$ is too short, for instance, it would be hard to ignite the pre-detonator.
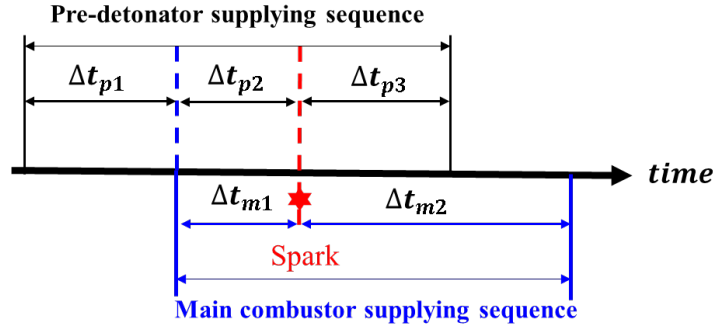


Figure 4 Time sequence

The high frequency of dynamic pressure of detonation wave in the combustor is captured by PCB. The maximum sensitive frequency of the pressure transducer is 500 kHz which is high enough to respond the pressure changes in the combustor.

## 3    Results and Discussions

In order to investigate the delay time of the experimental engine model, series of ignition tests were carried out with the different time interval $\Delta t_{p1}$. In the present experiments, in order to avoid the influence of flow in the main combustor before ignition, $\Delta t_{p2}$ and $\Delta t_{m1}$ are 0. The time interval $\Delta t_{p3}$ is also set to 0 to eliminate its effects after ignition.

The time interval $\Delta t_{p1}$ is varied to investigate its effects on delay time. Since the pre-detonator is connected to the main combustor, gas mixtures in the pre-detonator may also enter the main combustor before ignition. Therefore, it's possible to change the gas mixtures pre-filled in the main combustor by changing the time interval $\Delta t_{p1}$. Table 1 shows the operating conditions. The time interval $\Delta t_{p1}$ is changed from 0.1s to 0.3s, which in turn changes volume ratio of fresh gas mixtures pre-filled in the main combustor. As for the mass injected in the annular chamber, the mass flow rate of hydrogen is about 2-6 g/s while the mass flow rate of oxygen is about 15-20 g/s. As for the mass injected in the pre-detonator, the mass flow rate is about one eighth of that in the annular chamber.

Table 1: Operating Conditions

| Case | $\Delta t_{p1}$ (s) | Delay time (ms) |
|------|------|------|
| A | 0.1 | 13 |
| B | 0.2 | 28 |
| C | 0.3 | 53 |

Firstly, experiments were performed to demonstrate the feasibility of CDE with an array of injection holes. A close-up of the pressure histories in stable phase is shown in Fig. 5. Every time the CRDW swept over the sensor, a peak appeared in the pressure history. Through, the peak values of each pressure peak, which were determined by the strength of the CRDW, were not exactly the same. The time interval between two adjacent was around 131.4 μs. Assuming that there was one CRDW in the combustion chamber, the propagating velocity of the detonation wave was 1863 m/s, which agreed well with the C-J velocity. According to the profile of pressure history and propagating velocity, the feasibility of CDE with an array of injection holes has been demonstrated experimentally.
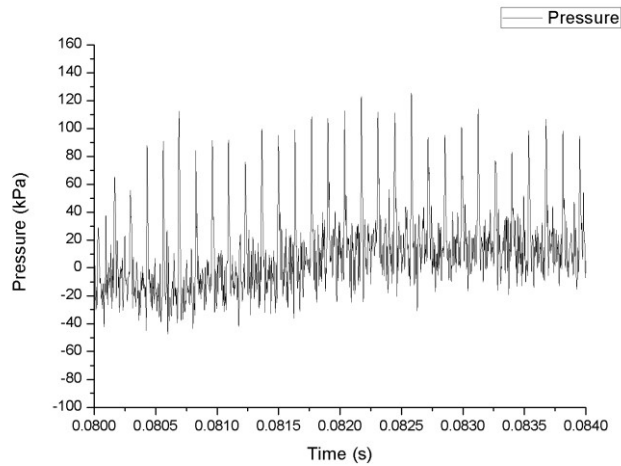
Figure 5 A  close-up of the pressure history in the steady section

Secondly, as shown in Fig. 6(a), (b) and (c), ignition takes place at 0.01s. The first pressure peak, which is marked by the red arrow in the left, represents the pressure in main combustor when the detonation wave generated in the pre-detonator entered the main combustor and ignited the gas mixtures in the main combustor. Although the strength of the initial detonation wave was pretty high, it took several milliseconds to form a stable CRDW. After that, it came to the stable stage when the detonation wave propagated circumferentially in the annulus. Since the time interval was increased, the volume ratio $\varphi$ of fresh mixtures was also increased in the main combustor. It was found that the delay time increased as the volume ratio $\varphi$ of fresh mixtures in the main combustor increased.  The possible explanation for the phenomenon is that the fresh mixtures prefilled in the main combustor ignited by detonation wave from pre-detonator resulted in complex flowfiled in the main combustor.  As the volume ratio $\varphi$ of the fresh mixtures increased, the energy released by the first explosion also rised. The fuel and oxidizer are fed by pressure difference between the manifold and main combustor. High pressure in the main combustor may block the gas feeding into the main combustor, making it hard to form the CRDW in the main combustor.
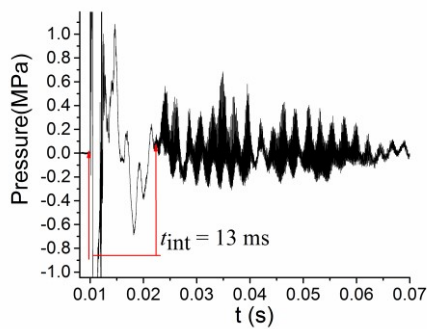


(a) Case A
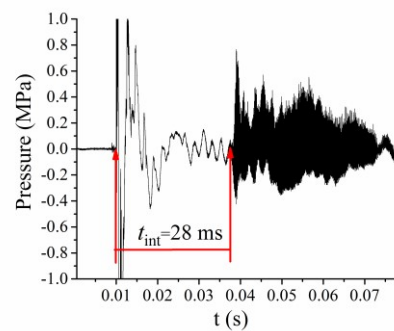


(b) Case B
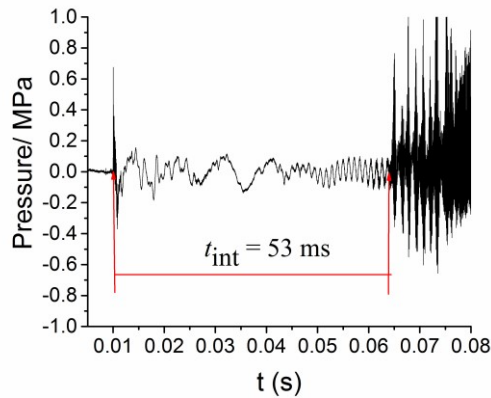
(c) Case C

Figure 6 Pressure Histories

## 4    Summary

An experimental study is carried out to investigate the delay time. An annular chamber combustor with an array of injection holes is designed for testing and pressure history is obtained during each shot. According to the analysis of the experimental data, several conclusions are obtained. The pressure history shows that CRDWs can be obtained in the combustor with an array of injection holes when hydrogen-oxygen is used. Delay time obtained in experiments increases when the prefilling time increase, which is an indicator the volume ratio $\varphi$ of gas mixtures pre-filled in the main combustor. Following numerical simulation are being conducted to investigate the delay time increases by changing the volume ration of the gas mixtures pre-filled in the combustor directly.

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