Experimental Research on Ignition and the Stabilization Process in Rotating Detonation Chamber

John Z. Ma, Yan Hao, Shujie Zhang, Jianping Wang*
Center for Combustion and Propulsion, CAPT&SKLTCS, Department of Mechanics and Aerospace Engineering, College of Engineering, Peking University,
Beijing, 100871, China

1 Background

Based on nearly isochoric combustion process, the detonation engine, especially the Rotating Detonation Engine (RDE), inherently enjoys higher thermodynamic efficiency and specific impulse compared to standard isobaric combustion process based gas turbines. Taking advantage of a self-compressing rotating detonation wave (RDW), the RDE can run as a simple and compact package. It is expected to break the bottleneck encountered by conventional deflagrations-based propulsion devices. Voitsekhoviskii [1] first proposed the basic concept of RDE. Figure 1 shows the wave structure of an RDW in RDE. Fresh propellants are fed into the co-axial annular combustor from the wall inlet. The detonation wave generated by the coupling of a leading shock and a chemical reaction zone propagates circumferentially in the annular combustor, followed closely by a contact discontinuity between freshly detonated products and older burnt products. The combustion products are exhausted at high velocity along the combustor outlet.

In previous studies, a great deal of research has been conducted on both single-wave and multi-wave phenomena. Fujii et al. [2] studied detonation velocity of the single-wave in RDE chamber with ethylene/oxygen mixture. Schwer et al. [3] achieved single-wave rotating detonations of different gaseous fuels and oxidants by numerical simulation, including hydrogen/air, ethylene/air, ethane/air, propane/air, ethylene/oxygen, ethane/oxygen, and propane/oxygen. Rankin et al. [4] captured the cellular structure of single-wave detonations with chemiluminescence imaging in an optically accessible non-premixed RDE. Yao et al. [5, 6] simulated the steady one-wave rotating detonations and the steady multi-wave rotating detonations. However, there is little research on ignition, especially the stabilization process of RDW. This paper presents experimental research on ignition and the stabilization process in hydrogen-air rotating detonation chamber with an array of injection holes.

2 Experimental System and Methodology

Correspondence to: wangjp@pku.edu.cn

Figure 2 shows a schematic of the experimental system, including a combustor, a gas supply system, an ignition system, a data acquisition system. Hydrogen and air are used as fuel and oxidizer, respectively.

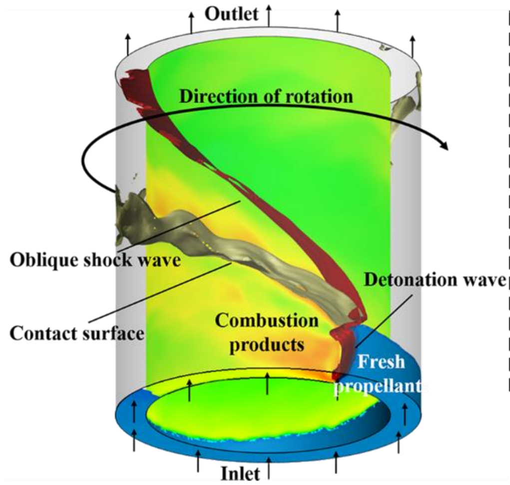


Fig.1 Wave structure of an RDW in RDE

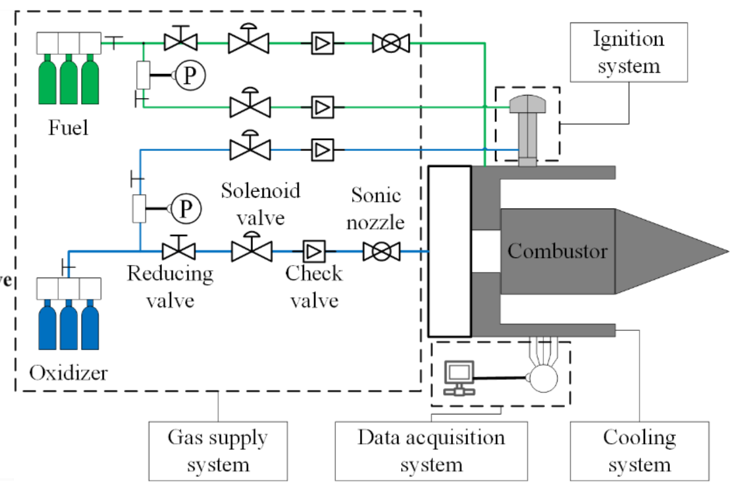


Fig. 2 Schematic of the experimental setup.

The gas supply system is made up of the source gas, gas supply lines, sonic nozzles, and valves. Six gas cylinders are used for air and hydrogen. Each cylinder has the volume of 40 L and the initial pressure is 13.5 MPa. The sonic nozzles are used to measure the mass flow rate of air and hydrogen. The reducing valves are able to maintain a constant pressure at the valve exit. The check-valves prevent backflow. Gas feeding is controlled by a solenoid-valve on every single pipeline. A computer program controls the solenoid-valves and the spark plug separately. The ignition system consists of a spark plug, an ignition loop, and a pre-detonator. The pre-detonator includes a spiral to promote flame acceleration. Deflagration to detonation transition (DDT) is completed in the pre-detonator. The pre-detonator needs to work only at the start of each run. The data acquisition system collecting pressure signals is comprised of the dynamic pressure sensors PCB113B22 and a data recorder. The maximum frequency response of the pressure transducer is 500 kHz, which is high enough to capture the pressure changes in the combustor. The sensitivity of the pressure transducer is 0.145 mV/kPa.

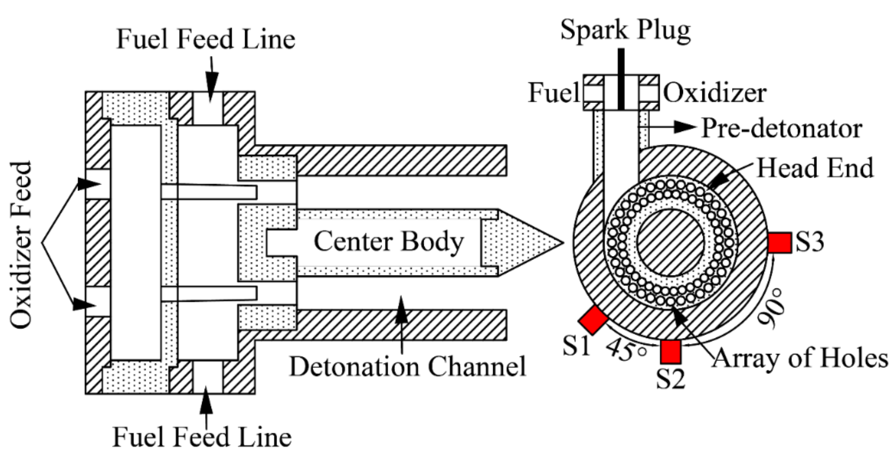
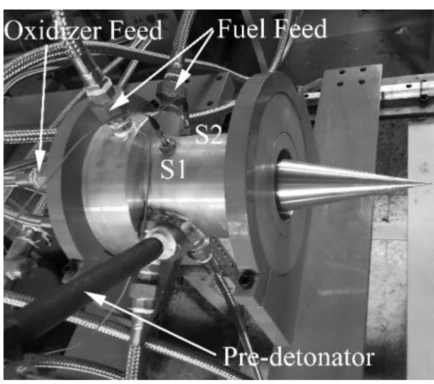


Fig. 3 Schematic of rotating detonation engine device with injection pattern and relative positions for pressure sensors shown.

Figure 3 shows a diagram of the rotating detonation engine device with an injection pattern and the relative positions of the pressure sensors. The inner-diameter d_i, outer-diameter d_o and length of the chamber are 59 mm, 79 mm and 124 mm respectively. The cone angle and diameter of the plug nozzle are 11 degrees and 59 mm respectively. The pressure sensors S1, S2 and S3 are set up along the outer wall of the combustor, which is 6 mm from the head end to the sensors. In the present research, 72 groups of coaxial tubes in the experiment were used to represent the array of injection holes. The diameter of inner tube in the coaxial tube is 2 mm and the diameter of outer tube is 3 mm. High pressure air injected from the inlet of the inner tube is mixed with the high pressure hydrogen injected from the hydrogen plenum, as shown in Figure 4. The injection via an array of holes for RDE was first proposed by Wang and its feasibility was demonstrated numerically by Yao et al. [7]. The injection pattern can increase the injection area and reduce the momentum loss from the injection process.

The experiments are conducted according to a specific time sequence as shown in Fig. 5. First, the hydrogen and air in the branch are fed into the pre-detonator. After a time interval Δt_{p1}, the hydrogen and air in the main line start to flow into the combustor, at the same time the hydrogen and air of pre-detonator are still supplied. After a time interval $\Delta t_{p2} = \Delta t_{m1}$, the premixed propellants in pre-detonator is ignited by a spark plug. After ignition, the hydrogen and air in the branch are fed into the pre-detonator for a time interval of Δt_{p3}. The time interval Δt_{m2} represents the test-time. The combination of time intervals should be precisely set, for example, if Δt_{p1} was too short, it would be hard to ignite the pre-detonator. In the present experiments, we set Δt_{p1} =100 ms, $\Delta t_{p2} = \Delta t_{m1}$ =100 ms. The time interval Δt_{p3} is set to zero to eliminate its effects after ignition. Burnt products are exhausted into the ambient environment. The mass flow rate of hydrogen injected in the annular chamber is between 0.5-3 g/s, while the mass flow rate of air is between 10-90 g/s. The mass flow rate injected in the pre-detonator is about one eighth of that in the annular chamber.



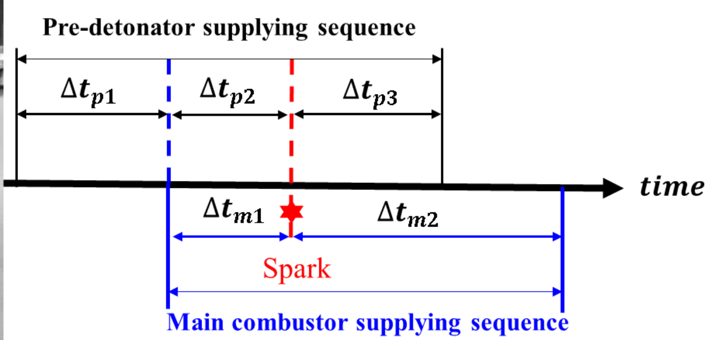


Fig. 4 Photograph of the combustor Fig. 5 Time sequence for the mixture injection and spark ignition

3 Results and Discussions

In fact, three pressure sensors were used in the experiments. After post-processing, it was found that the signals recorded by these three sensors are the same except for the time phase. Therefore, in order to facilitate the analysis of data, we only selected the data recorded by one of the pressure sensors. The rotating detonation wave in the combustion chamber can be divided into three modes based on its features of existence and self-sustaining, i.e., stable propagation mode, unstable propagation mode, and no detonation mode. Fig. 6 is the time history of pressure and time domain character in the RDW experiments, of which (a) is the pressure-time profile, (b) is the spectrogram plot via Wavelet transform (WT), (c) is the frequency-time profile of pressure via WT. The frequency-time profile of pressure is defined as the frequency corresponding to the maximum value of signal energy at each moment in the spectrogram. It represents the dominant frequency of the detonation wave pressure signal at that moment. According to the current experimental results, the stable mode can be zoned as two stages, i.e., self-adjusting stage and stable stage.

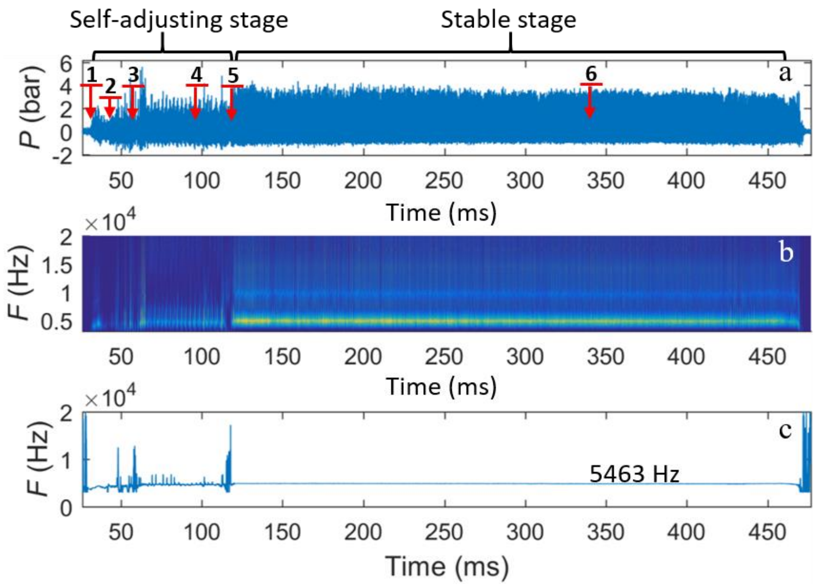


Fig. 6 Time history of pressure and time domain character of RDW. The total pressure $p_{air} = 1.6$ MPa, $p_{\mathrm{H_2}} =$ 0.6 MPa, the backpressure of the outlet $p_{ambient} = 1\ atm$, and the equivalent ratio $\phi = 1.0$.

A great deal of research has been done on the description of deflagration, stable detonation and unstable detonation, such as the Ref. [8] in the paper. Obviously, the precise definitions about stronger (weaker) detonation are complex and difficult. Stronger (weaker) detonation here refers to the relative intensity, that is, the height of the pressure peaks after detonation waves. Enlarging the details of the red bar areas in Fig. 6, we can see the stabilization process of RDW. Fig. 7 shows the entire stabilization sections of RDW, including deflagration, deflagration to detonation transition (DDT) process, the coexistence of detonation with deflagration, the coexistence of strong & weak detonations, unstable to stable detonation transition and stable detonation, which the self-adjusting stage includes the fore five sections. The first pressure peak shown in Fig. 7 (1) comes from the ignition by the pre-detonator. The detonation wave was not initiated in the combustion chamber at once, while a deflagration occurred. Then after a period of delay time, a weak detonation wave forms via a DDT process shown in Fig. 7 (2). The weak detonation wave cannot exist stably, but it becomes a coexistence of detonation with deflagration shown in Fig. 7 (3). Wang et al. [8] also describe this phenomenon. Then coexistence of strong & weak detonations appears as the detonation becomes stronger and the deflagration becomes weaker shown in Fig. 7 (4). Finally, after the transition from unstable to stable detonations, a stable detonation wave was formed in the combustor.

The reinitiation phenomenon occurred in Fig.8-9. As can be seen from the subplot (a), there is a phenomenon of coexistence of detonation with deflagration before quenching. Then after a period of time, detonations, however, were found to reinitiate spontaneously in the combustion chamber. The reinitiation process is similar to the stabilization process described above.

In order to study the effect of pressure variation on reinitiation, a series of experiments were conducted by changing the injection pressures of the propellant. As shown in Fig. 8, the quenching time is about 6.0 ms. The quenching time is about 2.5 ms as shown in Fig. 9. We can see that the quenching time reduces when increasing the injection pressures of the propellant. Then Fig. 7 presents that the phenomenon of quenching disappears when continuing to increase the injection pressures of the propellant. The reinitiation phenomenon is related to the injection pressures of the propellant. Increasing the injection pressure helps to reinitiate, thus avoiding the occurrence of the quenching phenomenon.

4 Summary

In this paper, an experimental study is performed on ignition and the stabilization process in hydrogen-air rotating detonation chamber with an array of injection holes. The main conclusions are as follows:

(1) The entire stabilization processes of RDW in stable mode include deflagration, deflagration to detonation transition (DDT) process, the coexistence of detonation with deflagration, the coexistence of strong & weak detonations, unstable to stable detonation transition and stable detonation.

(2) The reinitiation phenomenon is related to the injection pressures of the propellant. Increasing the injection pressure helps to reinitiate, thus avoiding the occurrence of the quenching phenomenon.

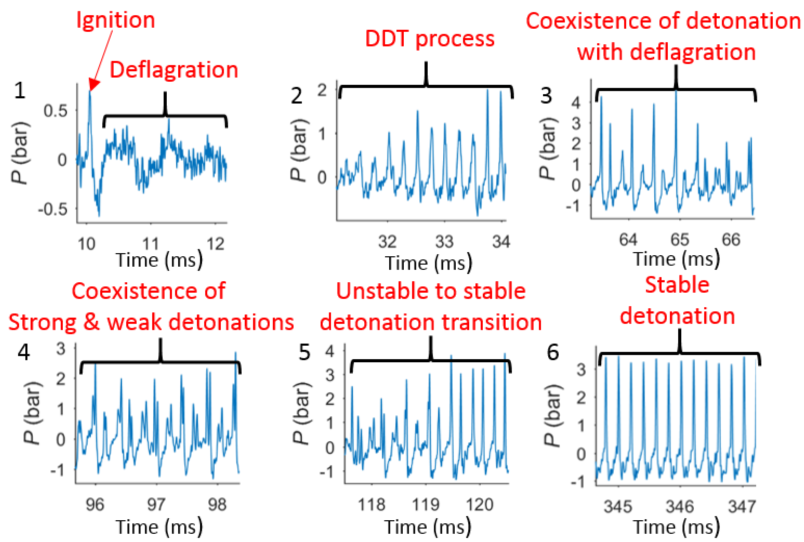


Fig. 7 Close-up of the pressure history in the red arrow areas in Fig. 6

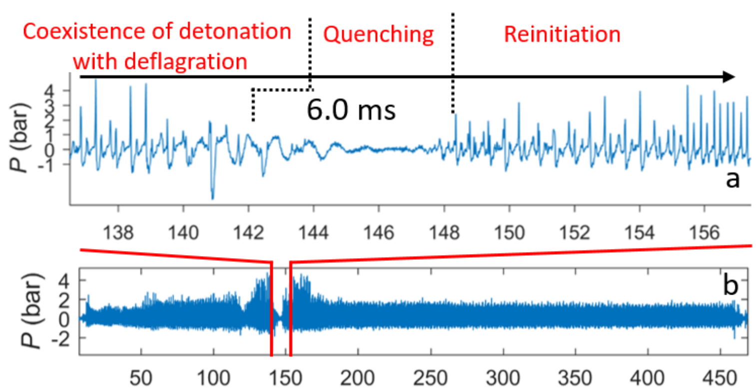


Fig. 8 The detail of pressure history. The total pressure $p_{air} = 1.0$ MPa, $p_{\mathrm{H}_2} = 0.4$ MPa, $p_{ambient} = 1\ atm$, and the equivalent ratio $\phi = 1.0$.

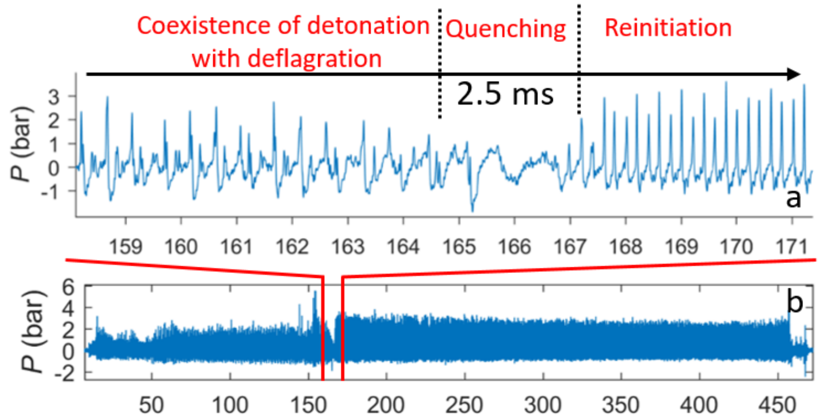


Fig. 9 The detail of pressure history. The total pressure $p_{air} = 1.3$ MPa, $p_{\mathrm{H}_2} = 0.5$ MPa, $p_{ambient} = 1\ atm$, and the equivalent ratio $\phi = 1.0$.

References

[1] Voitsekhovskii B. Maintained detonations. Sov J Appl Mech Tech Phys 1960;3:157–64.

[2] Fujii J, Kumazawa Y, Matsuo A, Nakagami S, Matsuoka K, Kasahara J. Numerical investigation on detonation velocity in rotating detonation engine chamber. Proc Combust Inst 2017;36:2665–72. doi:10.1016/j.proci.2016.06.155.

[3] Schwer D, Kailasanath K. Fluid dynamics of rotating detonation engines with hydrogen and hydrocarbon fuels. Proc Combust Inst 2013;34:1991–8. doi:10.1016/j.proci.2012.05.046.

[4] Rankin BA, Richardson DR, Caswell AW, Naples AG, Hoke JL, Schauer FR. Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine. Combust Flame 2017;176:12–22. doi:10.1016/j.combustflame.2016.09.020.

[5] Yao S-B, Liu M, Wang J-P. The Effect of the Inlet Total Pressure and the Number of Detonation Waves on Rotating Detonation Engines. Procedia Eng 2015;99:848–52. doi:10.1016/j.proeng.2014.12.611.

[6] Yao S, Liu M, Wang J. Numerical Investigation of Spontaneous Formation of Multiple Detonation Wave Fronts in Rotating Detonation Engine. Combust Sci Technol 2015;187:1867–78. doi:10.1080/00102202.2015.1067202.

[7] Yao, S., Han, X., Liu, Y., Wang, J.: Numerical study of rotating detonation engine with an array of injection holes. Shock Waves. 27, 467–476 (2017). doi:10.1007/s00193-016-0692-6

[8] Wang Y, Wang J. Coexistence of detonation with deflagration in rotating detonation engines. Int J Hydrog Energy 2016;41:14302–9. doi:10.1016/j.ijhydene.2016.06.026.