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Discovery of breathing phenomena in continuously rotating detonation

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Abstract

As is generally thought, continuously rotating detonation should keep going around the combustor regularly and has a fixed period. However, from the figures gotten by the data acquisition system, two kinds of breathing phenomena, Low Breathing and Deep Breathing, are discovered in the experiment. Actually they are caused by the changing mass flux, which stems from the pressure change in the combustor. The two kinds of breathing phenomena have different time scales and combustion mechanism. Reverse DDT is also discovered in one of the breathing phenomena. Since RDE is strong in thrust and high in efficiency, it has a great application foreground in the Aerospace Engineering.

Keywords: Continuously rotating detonation; Deep Breathing; Low Breathing; time scales

1. Introduction

Combustion includes two processes: deflagration and detonation. The propagating velocity of deflagration is subsonic while that of detonation is supersonic. Conventional engines usually use deflagration to generate heat and then do work. Compared with conventional engines, detonation engines work by detonation and the combustion is quick and strong. Taking advantage of nearly isochoric combustion process, detonation engines can achieve higher thermodynamic efficiency and higher specific impulse than conventional deflagration-based propulsion devices such as gas turbine engines and ramjets. Furthermore, detonation allows more intense and faster combustion, implying that comparatively small combustors are capable of creating enormous thrust. Moreover, it is simple, not requiring turbines or compressors. These benefits have gained worldwide interest in research into detonation engines.

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Now, how to design a detonation engine to create thrust becomes a challenge. The pulse detonation engine (PDE) has been widely investigated during the past quarter century. At present America, China, France, Russia and some other countries are doing research on PDE. Kailasanath [1] describes new progress of PDE. A team from the Air Force Research Laboratory [2] demonstrated the feasibility of a Pulse Detonation Engine (PDE) as a flight engine when the first manned, PDE-powered aircraft flew on 31 January 2008 in Mohave, California. Nevertheless, due to the inherent disadvantages such as the limitation of repeating frequency and mass flux, and the waste of unused detonation products, there is not a reliably-functioning pulse detonation engine having been developed up to now. The recently investigated continuous detonation engine (CDE), known also as the continuously rotating detonation engine (CRDE), provides an easier way to achieve detonation propulsion. As the detonation wave propagating direction and the fuel injection direction are independent, the detonation wave can continuously propagate in a wide range of injection velocity from low subsonic to supersonic [3] and need not multi-time ignition. These characteristics would greatly reduce the difficulties in the design of a detonation engine. Fig 1 shows the working mechanism of CRDE. The bold arrowhead is the flowing direction of the premixed gases. The detonation wave with a contact surface and an oblique shock wave is rotating perpendicularly to the flowing direction. The contact surface is the discontinuity between detonated products and older products.

The basic concept behind a CDE was first proposed by Voitsekhovskii [4]. Experimentally Voitsekhovskii achieved short-lived continuous detonation fuelled by acetylene. In the recent years, CDE has been extensively studied both theoretically and experimentally, by Bykovskii et al. [5-7]. Kindracki et al. [8] have experimentally obtained very promising thrust performances from a rocket-type RDE. In this paper, experimental devices and results on continuously rotating detonation engines are provided.

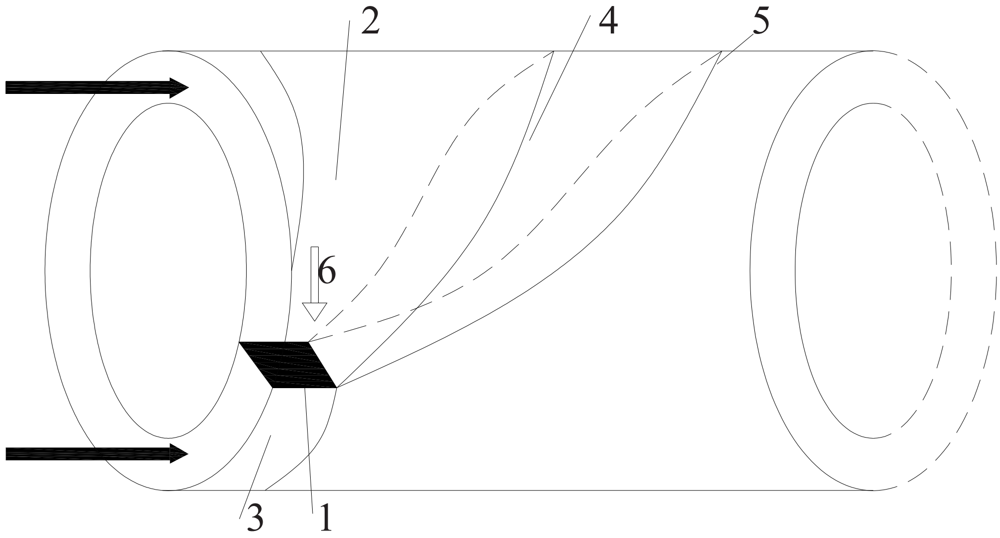

Fig.1. Working mechanism of continuously rotating detonation engines, 1-detonation front, 2-detonation products, 3-premixed gases, 4-contact surface, 5-oblique shock wave, 6-rotating direction of the detonation wave

2. Experimental setup

The experimental system mainly consists of the gas supply system, the exhausting system, the controlling system, the ignition system, the data acquisition system and the combustor. The gas supply system, which supplies hydrogen and oxygen to the combustor, includes gas source, reduction valves, checkvalves, solenoid valves, singlechip and some pipes. The reduction valve can keep a constant pressure rightly after itself. The checkvalve allows the gas to go only one way, which can avoid the back fire and ensure the safety. On and off of the solenoid valve are controlled by a singlechip. The exhausting system comprises a shock tube of length 2m and inner diameter 78mm, and a vacuum tank of $1.36m^3$. The detonation products are exhausted into the vacuum tank with an initial ambient pressure 20000Pa, which is low enough to prevent the observation window from being broken by the detonation wave. The vacuum tank can ensure the safety and reduce noises. The cooling system, the working medium of which is water, is mainly used on the pressure transducer to protect the transducer from the high flash temperature generated by continuously rotating detonation waves.

A spark plug, an ignition loop and a predetonator comprise the ignition system. The signal to ignite the premixed gas in the predetonator is also given by the singlechip. Deflagration can become detonation through the predetonator, as is called Deflagration to Detonation (DDT).This system is used to initiate the detonation wave in the combustion chamber, which will keep rotating circumferentially. Data acquisition system acquiring pressure signals mainly consists of the PCB dynamic pressure transducers and a data recorder. Frequency tailoring and the very high natural frequency of the sensor give an extremely wide usable frequency range (beyond 400 kHz). Fast response time (shorter than 1.5 microseconds) and clean, virtually non-resonant response to rapid step functions are also features of the sensor. The measurement range is 34.5MPa, enough to measure the detonation pressure of hydrogen and oxygen.

Continuously rotating detonation goes ahead in the combustor. Hydrogen and oxygen mix at the head of the combustor and then in the middle of the combustor the premixed gases are burnt by detonation waves, which are initiated by the predetonator. To keep the annular structure from distorting, three small bolsters are used at the end of the combustor, not interfering the rotating detonation waves basically.

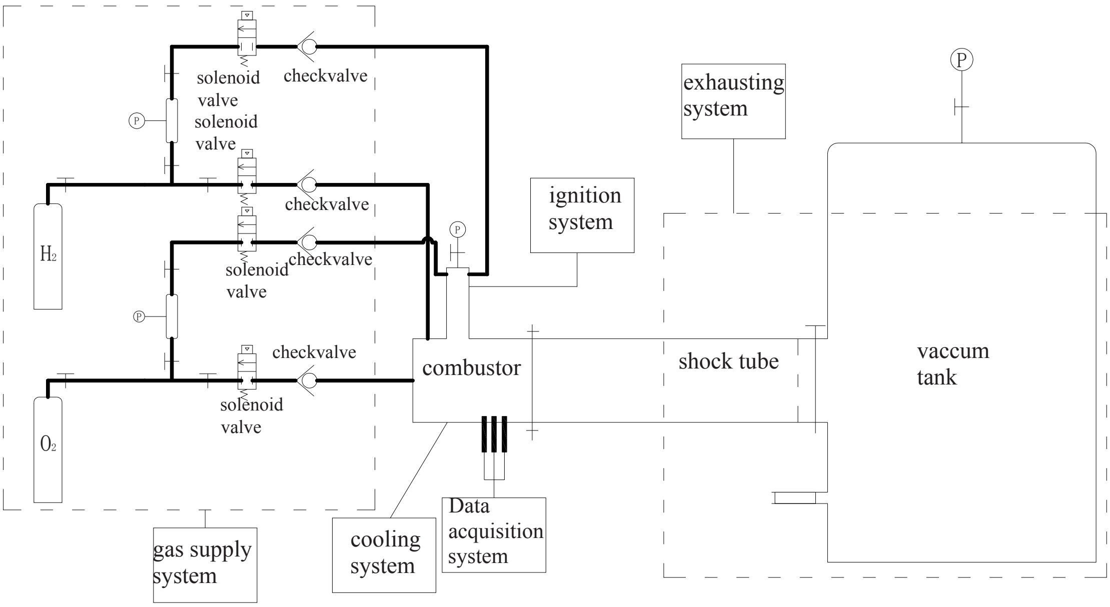

Fig.2. Experimental system

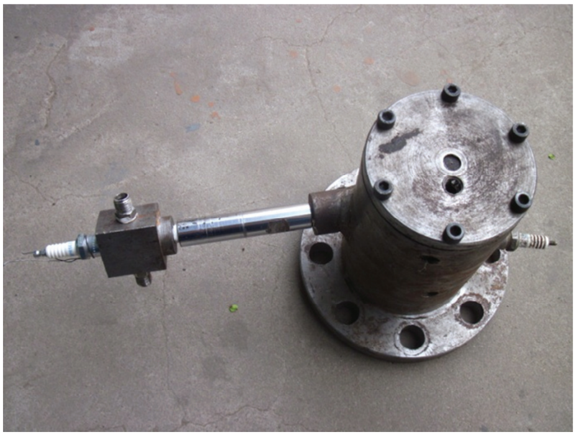

Fig.3. The combustor with a predetonator.

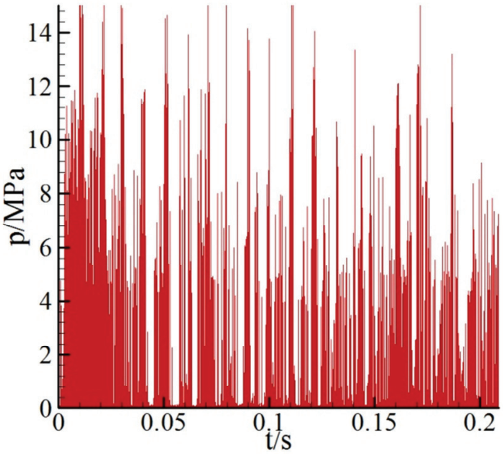

Fig.4. Global view of detonation pressure history acquired by the pressure sensor

The detonation experiment is performed in the annular combustor which is shown in Fig 3.The chamber has the following geometric parameters: inner diameter d_i=58mm, outer diameter d_o=78mm, length l_{ch}=60mm, channel width 10mm. The distance from the mixture inlet to the ignition place is 15mm. Though the combustor is made of stainless steel, it is still strongly affected with rust because of high detonation temperature and water produced by combustion.

Controlled by the singlechip, the spark plug ignites the gases 0.2s after the gas supply. The temperature and total pressure of hydrogen and oxygen are respectively 300K/300K,0.7MPa/0.75MPa.

3. Results and Discussions

3.1. The number and frequency of detonation waves

As is predicted, the experimental results are shown in Fig 4 and 5. From Fig 5 it is seen the period in the experiment is t_e=0.016ms.

The simplified C-J detonation velocity formula [9] is

$$D_J - u_0 = \pm\sqrt{2(\gamma_1^2 - 1)Q} \tag{1}$$

D_J - The detonation velocity, u_0 - the cross velocity of the fresh gas, γ_1 - specific heat ratio of detonation products, Q-the heat that 1kg fresh gas releases by combustion.

In the experiment,

u_0=0, γ_1=1.135, $Q = 1.34\times10^7 J/kg$.

Then the detonation velocity is calculated, D_J =2783m/s. If there is only one detonation wave rotating in the combustor, the period of the detonation wave is

$$t_o = \pi d_{ch} / D_J \tag{2}$$

The wave-number formula of detonation is

$$n = t_o / t_e = \pi d_{ch} / (D_J t_e) \tag{3}$$

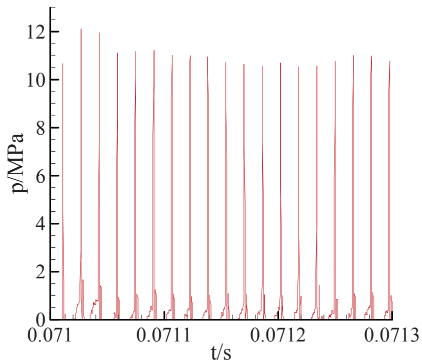

Fig.5. Local view of detonation pressure history

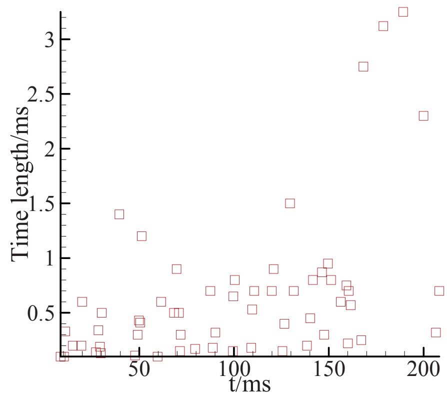

Fig.6. Continuous time length of the detonation wave of 62500Hz

t_e -The period of the detonation wave in the experiment, d_{ch}-the average diameter of the annular channel of the chamber.

Putting the datum in the formula (3), the number of detonation waves is gotten

$$n = \frac{\pi d_{\mathrm{ch}}}{D_{\mathrm{J}} t_{\mathrm{e}}} = \frac{3.14 \times 68 \times 10^{-3}}{2783 \times 16 \times 10^{-6}} \approx 5 \tag{4}$$

Five detonation waves are rotating in the chamber, exhausting the fresh gas greatly. Put n=5 back to the formula (3), and the actual velocity of detonation waves is obtained as followings.

$$D_J^e = \frac{\pi d_{ch}}{n t_e} = \frac{3.14 \times 68 \times 10^{-3}}{5 \times 16 \times 10^{-6}} m/s = 2669 m/s$$

It is a little different from the theoretic velocity 2783m/s. One reason is that the flow before detonation is theoretically one-dimensional while the real flow is three-dimensional; another is that parameters of hydrogen and oxygen in the experiment do not accurately match the values of the theory.

In the experiment, the frequency of detonation waves is

$$f = \frac{1}{t_e} = \frac{1}{16} \times 10^6 Hz = 62500 Hz \tag{5}$$

The detonation of highest frequency is mainly distributed at the time shown in Fig 6 while the frequency of other time is smaller. Most points are between 0.3ms~1ms, which indicates that generally the pressure in the combustor could be changed so greatly that the intensity and the number of detonation waves begin to decrease because of reduced flux if the continuous detonation lasts for 0.3ms~1ms. As can be known, a lot of energy is collected at the time of the highest frequency and chemistry reactions go ahead strongly. The breathing phenomenon also occurs in the experiment of continuously rotating detonation in Fig 4, which is interesting and worth researching further.

3.2. Low Breathing

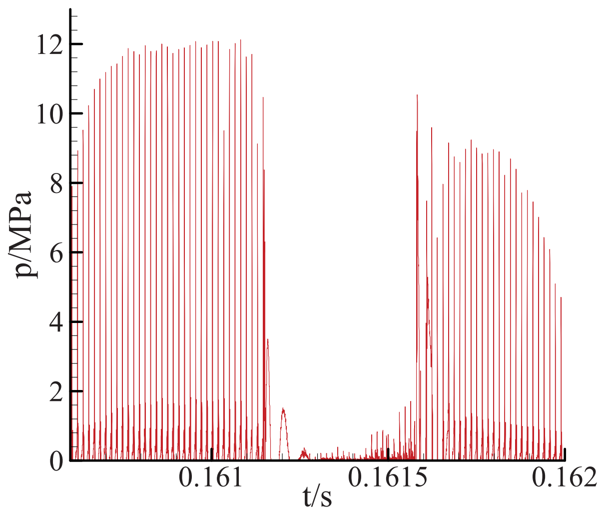

Fig.7. Low Breathing

The Low Breathing intervals vary from 0.08ms to 0.25ms, such as the interval △t between 161.2ms~161.45ms in Fig 7. According to

$$v = \pi d_{ch} / \Delta t \quad , \tag{6}$$

the velocity range is over 850m/s, which indicates that it is still detonation that is going on in the combustor, but much weaker than C-J detonation because the velocity of detonation is supersonic while the velocity of deflagration is subsonic. The sonic velocity in the hydrogen and oxygen mixture with the room temperature and pressure is about 540m/s and mainly depends on the equivalent ratio between the fuel and the oxidizer. The number of rotating detonation waves will increase with the mass flux in a certain range when some destabilization, such as shock waves or turbulence, happens to the detonation waves [10].

Actually, the inlet pressure is almost constant, which is controlled by a reduction valve while the average pressure $p_{\rm com}$ and the average temperature $T_{\rm com}$ in the combustor will change after a period. When the continuous detonation goes on for a moment, $p_{\rm com}$ and $T_{\rm com}$ will increase. As a result, the mass flux of working medium reduces, which makes the intensity and the number of rotating detonation waves decrease. Thus, the average velocity of detonation waves decreases and an evident time interval appears such as in Fig 7, as is called Low Breathing. This in turn reduces the pressure $p_{\rm com}$ and $T_{\rm com}$ which meanwhile promotes the increase of the mass flux of working medium. So the intensity and the number of detonation waves are recovered, and the figure of detonation waves becomes dense again. Just like this, the denseness and the sparseness in the figure of detonation pressure history appear by turns. Evidently since the flux is changing continually, continuous detonation is not stationary in the whole process but stationary during every group of steady rotating detonation waves. So the nature of Low Breathing is weaker detonation with a smaller velocity and a smaller number of detonation waves than steady detonation.

3.3. Deep Breathing

Deep Breathing is shown in Fig 4 and 8, such as at about 43ms, 53ms, 63ms and so on. Calculated from the detonation pressure history, the time intervals △t of Deep Breathing vary from 0.46ms to 3.36ms when the combustion goes ahead, which is shown in Fig 9. According to the formula (6) and Fig 9, a subsonic velocity range of 66m/s~141m/s is calculated. Therefore it’s the deflagration wave that is rotating during the interval. This conclusion is not at all surprising. Actually reverse Deflagration to Detonation Transition (DDT) [11] causes the deflagration wave. Reverse DDT is mainly caused by the same reason as that of low breathing and poor equivalent ratio in addition. However, the flux reduces more greatly than that of Low Breathing and the equivalent ratio becomes poorer, which causes reverse DDT but not only makes the intensity and the number of detonation waves decrease. After Deep Breathing, DDT starts because of the increasing flux of fresh gas and good equivalent ratio.

Reverse DDT, deflagration waves, DDT and continuously rotating detonation waves always occur by turns in the detonation experiment. From Fig 9, it can be seen that generally the time interval increases first and then deceases, and most time intervals are shorter than 1.5ms, which indicates that the fuel is combusting comparatively quickly during the breathing. This makes continuously rotating detonation have a greater power. As for combustion, Deep Breathing is deflagration while Low Breathing is weak detonation. The flicker of the flame at the end of the combustor shown in Fig 10 further supports breathing phenomena.

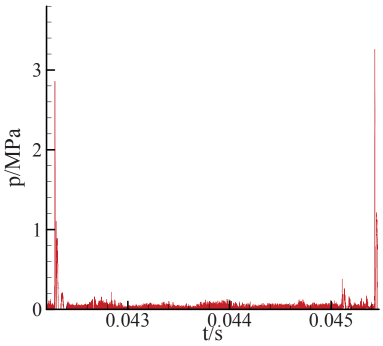

Fig.8. Deep breathing

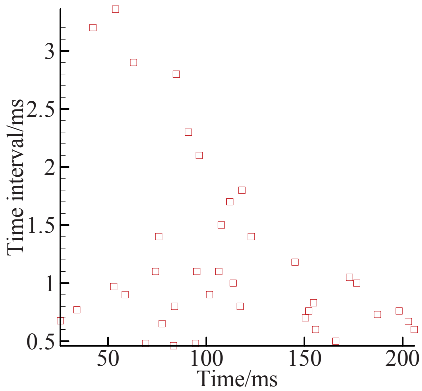

Fig.9. Time interval of Deep Breathing

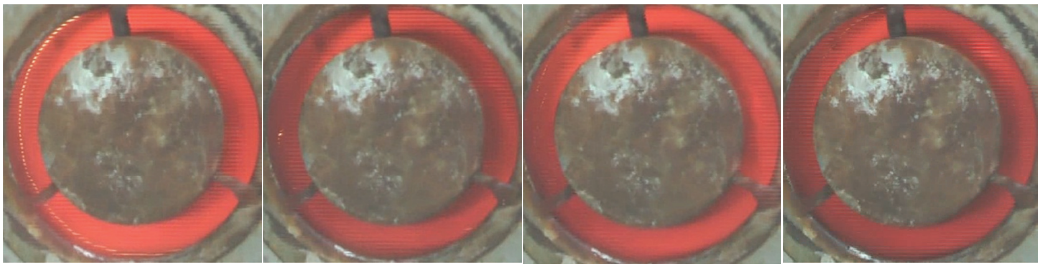

Fig.10. The flickering flames at the end of the combustor recorded by Digital Video

4. Conclusion

Generally, when the mass flux of working medium is not controlled rapidly enough, the experiment of continuously rotating detonation waves usually comprises Low Breathing and Deep Breathing, which is namely the self-sustaining mechanism of unsteady CRDE. Low Breathing is weaker detonation with a smaller velocity (but supersonic) and a smaller number of rotating detonation waves than steady rotating detonation waves. Deep Breathing is deflagration with a subsonic velocity and reverse DDT happens at Deep Breathing. As is concluded, the system of closed loop can reduce the breathing phenomenon, if the pressure change in the combustor could be fed upriver to change the flux of working medium quickly enough.

Acknowledgements

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