Experimental study on the aluminum powder rotating detonation engine

Han Xu, Chunsheng Weng, Quan Zheng
National Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing, Jiangsu, China

1 Introduction

Detonation engine is a kind of promising engine that have a higher thermal efficiency and a simpler engine structure [1], which is widely studied in recent years. Based on its operating principle, the detonation engine can be classified as the PDE (Pulse Detonation Engine), the RDE (Rotating Detonation Engine) and the ODE (Oblique Detonation Engine). Based on its application, the detonation engine can be classified as the rocket detonation engine, the air breathing detonation engine and the combining detonation engine. Most of these detonation engine researches were focused on gaseous fuels or liquid fuels. However, seldom researches were conducted on detonation engines fueled with solid fuels. The reliability and innate simplicity of solid propellant engines make them still attractive for most practical applications [2]. For instance, the solid propellant engines do not need complicated and lengthy pre-firing preparations to fill the propellants before firing and some solid propellants almost have no volatile, corrosive or cryogenic problems. On the other hand, the solid fuel has a higher energy density (chemical energy per volume). If adopt the solid fuel in the detonation engine, the advantages of both the detonation cycle and the solid fuel would be combined together to give a specific superiority to the solid fuel detonation engines. Bykovskii et al. [3–5] realized the detonation burning of a coal-hydrogen-air mixture in a RDE. Furthermore, they compared and analyzed the detonation combustion of different types of fossil coal powders [6]. Recently, Dunn et al. [7–11] have conducted experiments on a coal-driven RDE and found that the addition of the coal powder could broaden the operational regimes of the engine. However, the above researches were all based on the coal powder, which needs the hydrogen to sustain a rotating detonation wave. Without the hydrogen, the coal powder RDE would fail, which is a disadvantage to the propulsion application. This research aims at the aluminum powder RDE, which can sustain a rotating detonation wave with the pure air. The experimental results could provide a feasible solution for the air breathing aluminum powder RDE and establish a foundation for the solid powder RDEs.

2 Experimental Setup

The aluminum powder RDE is in a planar disk-shaped structure as shown in Figure 1. The fuel and air are injected into the planar combustor through the outer circle. The diameter of the planar combustor is 150 mm. The fuel injected into the combustor can be the aluminum powder or the hydrogen. If the

Correspondence to: xuhan@njust.edu.cn

aluminum powder is injected into the combustor with the air, the Al/Air RDE can be studied; if the hydrogen is injected into the combustor with the air, the H_2/Air RDE can be studied. Both the Al/Air RDE and the H_2/Air RDE were experimentally studied in this research to facilitate the comparison of the detonation characteristics and the propulsion performance between the Al/Air RDE and the H_2/Air RDE. The detonation products are ejected through the inner circle with a high speed to generate a thrust. The diameter of the inner circle is 50 mm. A pre-detonator is installed on one side of the chamber to generate a primary detonation wave. Such detonation wave enters into the planar chamber and propagates along the outer wall of the chamber. Consequently, a rotating detonation wave would be formed. For the convenience of the comparison, both of the Al/Air RDE and the H_2/Air RDE adopt the equivalence ratio of 1 and the air mass flow rate of 260 g/s. The aluminum powder is grounded to 0.5 μm as shown in Figure 2.

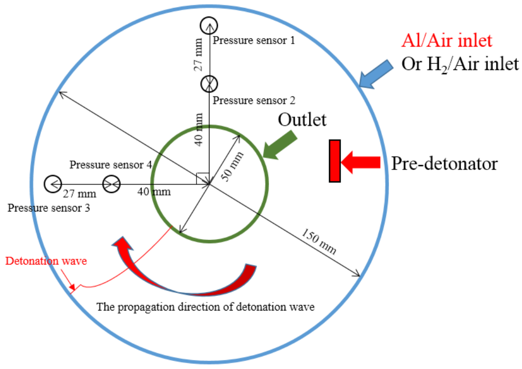

Figure 1: The schematic diagram of the rotating detonation combustor.

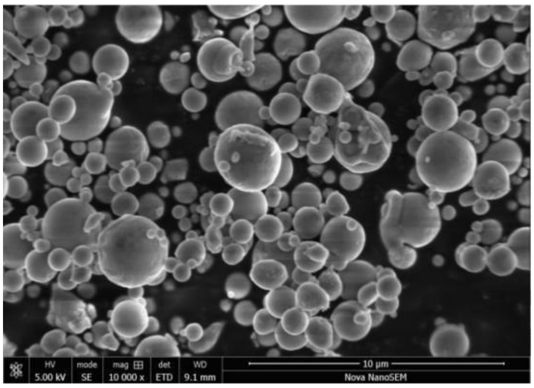

Figure 2: The SEM (Scanning Electron Microscopy) photos of the aluminum powder.

Four high-frequency piezoelectric pressure sensors are flush-mounted in the planar disk-shaped combustor to obtain the detonation characteristics. Pressure sensor 1 and 3 are mounted 67 mm away from the center of the engine, whereas pressure sensor 2 and 4 are mounted 40 mm away from the center of the engine. Defining the azimuth of the sensor 1 and 2 as 0°, the sensor 3 and 4 are located at -90°. The model of these four pressure sensors is PCB 113b24, of which the resolution is 0.035 kPa. The resonant frequency of the sensor is more than 500 kHz and the rise time is shorter than 1μs. The sampling frequency of the acquisition system is as high as 500 kHz for each channel, which could guarantee the capture of the detonation behavior. The thrust of the engine is obtained by a force sensor PCB 208C03, of which the resolution is 0.02 N.

3 Results and Discussion

The working process of the Al/Air RDE and the H_2/Air RDE is separately shown in Figure 3 and Figure 4. Both of engines would go through the process of pre-injection, ignition, working and quenching. Comparing these two engines, it can be seen that the pre-injection of Al/Air RDE would produce a mass of powder cloud. The ignition of the Al/Air RDE is more violent and the luminous intensity is much higher than that of the hydrogen.

Figure 3: The working process of the Al/Air RDE.

Figure 4: The working process of the H_2/Air RDE.

The pressure profiles separately in the Al/Air RDE and the H_2/Air RDE obtained by the pressure sensor 3 are shown in Figure 5. Every pressure rise represents the passage of the detonation wave and the pressure peak could represent the detonation intensity. It can be seen that the detonation intensity of the Al/Air is slightly higher than that of the H_2/Air, which may result from the higher energy density of the aluminum powder.

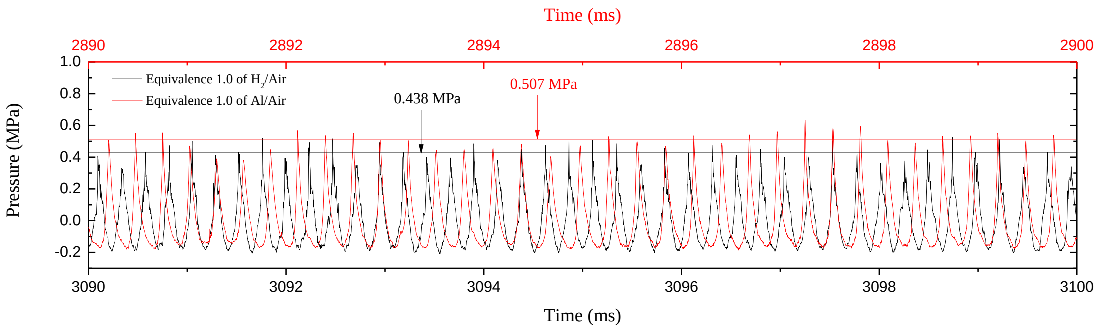

Figure 5: The pressure profiles separately in the Al/Air RDE and the H_2/Air RDE obtained by pressure sensor 3.

Figure 6 gives the FFT (Fast Fourier Transform) analysis of the Al/Air RDE and the H_2/Air RDE. It can be seen that the operating frequency of Al/Air RDE is lower than that of the H_2/Air RDE, which indicates that the detonation velocity of the Al/Air is lower than that of the H_2/Air.

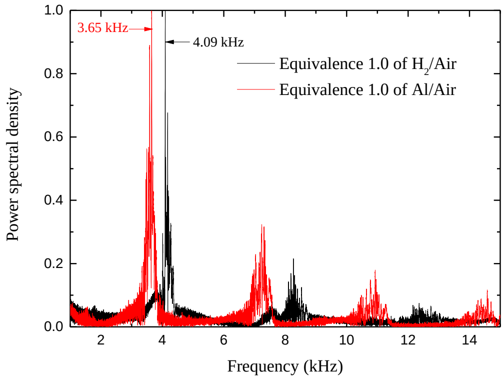

Figure 6: The Fast Fourier Transform plots of the Al/Air RDE and the H_2/Air RDE.

Figure 7 and Figure 8 shows the pressure profiles obtained by all four pressure sensors separately in the operation of the Al/Air RDE and the H_2/Air RDE. The location of these four pressure sensors can be found in Figure 1. For both engines, the pressures vary in regular oscillations, and pressure peaks repeat in "Pressure sensor 3 (Pressure sensor 4)→Pressure sensor 1 (Pressure sensor 2)", propagating in a clockwise direction. Such propagation is stable throughout the whole operation of both engines. As the pressure sensor 3 and 4 are on the same azimuth location, they almost simultaneously obtain the pressure peak, so as the pressure sensor 1 and 2. The number of the rotating detonation waves can be obtained by the following equations:

$$\Delta t_n = \frac{\pi D}{v_D} \cdot \frac{1}{n} \tag{1}$$

$$\Delta t_n' = \frac{\pi D}{v_D} \cdot \frac{\theta}{2\pi} \tag{2}$$

$$\mathrm{n} = \frac{2\pi}{\theta} \cdot \frac{\Delta t_n'}{\Delta t_n} \tag{3}$$

Δt_n and $\Delta t_n'$ are the time interval marked in Figure 7 and Figure 8; D is the diameter of the combustor; v_D is the velocity of the detonation wave; θ is the circumferential angle between pressure sensor 1 and 3, which is $\frac{\pi}{2}$; n is the number of the rotating detonation wave. $\frac{\Delta t_n'}{\Delta t_n}$ is estimated as 1/4, and thus n is calculated as 1, indicating that the propagation mode of both the Al/Air RDE and the H_2/Air RDE is a single wave.

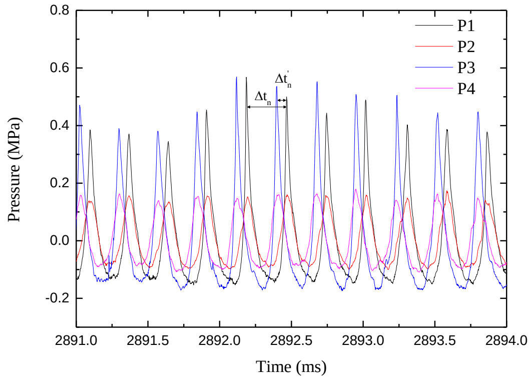

Figure 7: The pressure profiles in different positions of the Al/Air RDE.

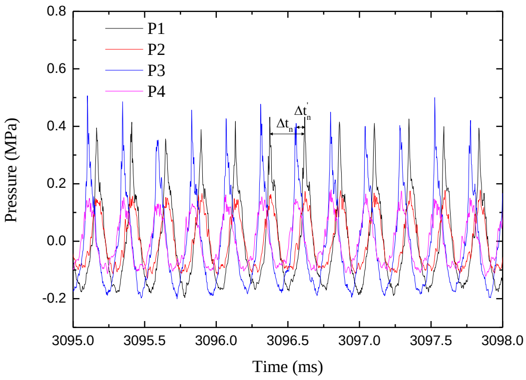

Figure 8: The pressure profiles in different positions of the H_2/Air RDE.

Figure 9 gives the thrust profiles of the Al/Air RDE and the H_2/Air RDE. The average thrust values for both engines marked in Figure 9 is calculated by the Eq. (4):

$$Thrust_{average} = \frac{\int_{t_1}^{t_2} Thrust(t)\Delta t}{t_2 - t_1} \tag{4}$$

$Thrust_{average}$ is the average thrust value; $Thrust(t)$ is the thrust value varied with the time; t_1 is the moment when the thrust reaches the maximum value; t_2 is the moment when the fuel supply is stopped.

It can be seen that the average thrust of the Al/Air RDE is 35% higher than that of the H_2/Air RDE, which may result from the higher energy density of the aluminum powder. It's noted that the initial thrust increase of 35 N is caused by the pre-injection of the Fuel/Air and the following thrust increase is caused by the detonation combustion of the Fuel/Air.

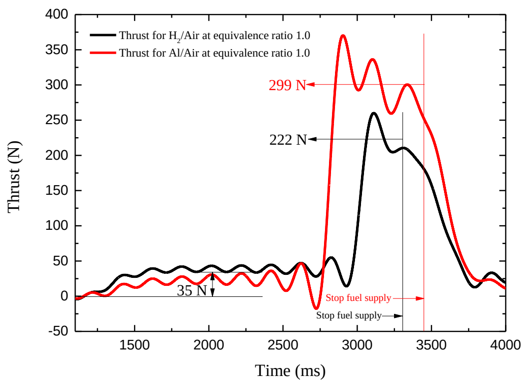

Figure 9: The thrust profiles of the Al/Air RDE and the H_2/Air RDE.

4 Conclusion

The operation of the Aluminum/Air rotating detonation engine is experimentally realized. Compared with the Hydrogen/Air rotating detonation engine at the same equivalence ratio of 1, the Aluminum/Air rotating detonation engine could generate a higher thrust; the detonation intensity of the Aluminum/Air is higher than that of the Hydrogen/Air; the detonation velocity of the Aluminum/Air is lower than that of the Hydrogen/Air; the detonation propagation mode of the Aluminum/Air is the same with that of the Hydrogen/Air: single wave mode. The experimental results could provide a feasible solution for the air breathing aluminum powder RDE and establish a foundation for the solid powder RDEs.

5 Acknowledgement

The authors acknowledge the financial support from the National Natural Science Foundation of China [No. 12002167]; the Natural Science Foundation for Young Scientists of Jiangsu Province of China [No. BK20190468] and the Fundamental Research Funds for the Central Universities [No. 30919011259; 309190112A1].

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