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Spectral analysis and self-adjusting mechanism for oscillation phenomenon in hydrogen-oxygen continuously rotating detonation engine

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Abstract The continuously rotating detonation engine (CRDE) is a new concept of engines for aircraft and spacecraft. Quasi-stable continuously rotating detonation (CRD) can be observed in an annular combustion chamber, but the sustaining, stabilizing and adjusting mechanisms are not yet clear. To learn more deeply into the CRDE, experimental studies have been carried out to investigate hydrogen-oxygen CRDE. Pressure histories are obtained during each shot, which show that stable CRD waves are generated in the combustor, when feeding pressures are higher than 0.5 MPa for fuel and oxidizer, respectively. Each shot can keep running as long as fresh gas feeding maintains. Close-up of the pressure history shows the repeatability of pressure peaks and indicates the detonation velocity in hydrogen–oxygen CRD, which proves the success of forming a stable CRD in the annular chamber. Spectrum of the pressure history matches the close-up analysis and confirms the CRD. It also shows multi-wave phenomenon and affirms the fact that in this case a single detonation wave is rotating in the annulus. Moreover, oscillation phenomenon is found in pressure peaks and a self-adjusting mechanism is proposed to explain the phenomenon.

1. Introduction

The heat releasing process in detonation is nearly isochoric. The isochoric Humphrey cycle has inherently higher thermodynamic efficiency than the isobaric Brayton cycle of deflagration, which is now widely used in engine combustion. When the compression ratio is 12, the thermal efficiency of Humphrey cycle is 18% to 37% higher than Brayton cycle in the combustion of hydrogen–oxygen mixture,[1] and 20% to

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40% higher in the combustion of hydrocarbon–air mixture.[2] In addition, according to Wolański,[3] Fickett-Jacobs cycle for heat addition in detonation mode can reach even higher thermal efficiency than Humphrey cycle. Therefore, it is believed that engines based on detonation have a bright future, and pulse detonation engines (PDEs) have been studied for decades. On the other hand, in recent years, continuously rotating detonation engines (CRDEs) have become a new hot point in detonative propulsion.

The basic concept of CRDEs was first proposed by Voitsekhoviskii,[4] and he experimentally achieved short-lived continuous detonation fuelled by acetylene. In recent years, CRDE has been extensively studied both numerically and experimentally. Kindracki et al.[5] have experimentally obtained promising thrust performances. During the past few years, Innovative Scientific Solutions Inc.,[6] Air Force Research Laboratory,[7] and several other organizations have been making effort to visualize CRDEs. Multi-waves mode in a continuously rotating detonation wave (CRDW) is found and studied by Bykovskii et al.[8] and Liu et al.,[9] individually. Wang et al.[10] found that when there are both axial flow from the head end of the combustor and tangential flow from the pre-detonator after deflagration to detonation transition (DDT), CRDW will split into a main detonation wave and several detonation wavelets, and lead to much lower velocity of the CRDW.

Besides of experimental research, many numerical simulations of the CRDWs are carried out. Shao et al.[11–13] performed comprehensive three-dimensional numerical simulations in CRDWs. They obtained multi-cycles of CRDWs and discussed several key issues, including the fuel injection limit, self-ignition, thrust performance and nozzle effects. Yamada et al.[14] numerically analyzed the propagation limit in hydrogen-oxygen rotating detonation and obtained its lower and upper threshold pressure. Schwer and Kailasanath[15] numerically studied the role of inlet stagnation pressure and back pressure on the rotating detonation characteristics and engine performance, and found that the detonation wave height and mass flow rate are determined primarily by the stagnation pressure, whereas overall performance is closely tied to pressure ratio.

Zhou and Wang[16] numerically studied the thermodynamic performance, showing that in a two-dimensional CRDE without a nozzle, inside of which 23.6% fuel is burned by deflagration and the thermal efficiency is around 39.7%. As the proportion of detonation combustion increases and a nozzle is attached at the exit, the thermal efficiency will be close to the ideal ZND (Zeldovich-von Neumann-Döring) model, which is 52.9%, theoretically. Frolov et al.[17] did the numerical simulation with effects of finite rates of turbulent and molecular mixing among combustible mixture components with each other and with reaction and detonation products. Liu et al.[18] firstly found multi-wave mode in numerical simulation with different injection patterns.

The previous experimental studies on continuously rotating detonations (CRDs) mostly concentrate on generating a stable CRD under various conditions and with different fuel-oxidizer combinations, or even to generate thrust for applications. Only a few studies have been done to investigate the mechanism and stability of the CRD. In the present study, we find the pressure oscillation phenomenon and try to give a reasonable explanation. Therefore, this study takes a further step into the mechanism of how a CRD keeps stable.

2. Experimental setup

2.1. Basic model

The combustion chamber of a CRDE is an annular chamber. A brief model is shown in Fig. 1. As fresh reactants are fed in at the head end, and the products exhaust out from the exit, a detonation wave keeps propagating circumferentially right against the head end. In front of the detonation wave, there is an area filled with fresh reactants, while behind the detonation wave are the products. Downstream inside the chamber, there are contact surfaces, oblique shock wave, and expansion waves, which enhance the ejection of the detonation products.

It is known from numerical simulations[12] that there is a region right behind the detonation wave, where the pressure reaches very high values. Since the fresh reactants-feeding is driven by pressure difference, the high pressure inside the chamber stops the feeding in that region. It is instinct that a stronger detonation wave ends up with higher pressure behind wave front, and would lead to a larger non-feeding region. And this may have a significant effect on the rotating detonation.

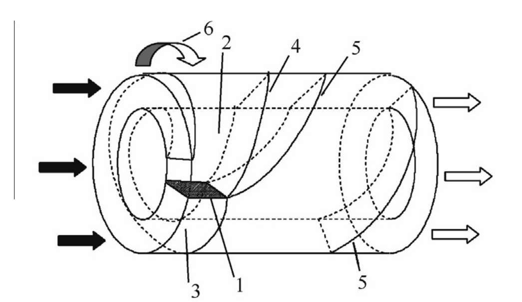
2.2. Experimental facilities

The entire experimental setup is shown in Figs. 2–4, including gas supplying system, combustion chamber, igniting system, exhausting system, and data collecting system.

It is designed to use hydrogen as fuel and oxygen as oxidizer. The fuel-oxidizer combination is chosen for its simple chemical model in combustion, easy-operating, and safe guarantee. Hydrogen is more active than most hydrocarbon fuels, and less reactive than ethylene, which provides a good balance between safety and easiness to generate a detonation wave. Designed as a rocket type engine rather than an air-breathing one makes the oxygen a direct choice.

The CRDE combustion chamber used in this study is an annular chamber with outer diameter 79 mm, inner diameter 59 mm, and length 100 mm. Pre-mixed fuel and oxidizer are fed into the combustor at the head end. A detonation wave propagates circumferentially in the annulus at the head end, while the burnt gas exhausts out of the chamber at the downstream exit.

The pre-mixed detonable gas in the main combustor is ignited by a pre-detonator connected to the combustor cylinder tangentially. The pre-detonator is also filled with hydrogen



1—Detonation wave; 2—Products ; 3—Fresh detonable mixture; 4—Contact surface; 5—Oblique shock; 6—Propagating direction of the detonation wave

Fig. 1 Model of a CRDE.