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Three-dimensional numerical investigations of the rotating detonation engine with a hollow combustor

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ABSTRACT

The aim of this work is to numerically verify a new model of the rotating detonation engine (RDE) combustor. The new model, which we call the hollow combustor, has no inner wall and is hollow. It is presented to solve the problem of engine heating that arises in RDEs with the co-axial annular combustor. Using the one-step chemistry kinetic model and the Euler equations in cylindrical coordinates, a series of three-dimensional (3D) numerical simulations are performed to find out whether detonation waves can propagate in such combustors. The results show that this new RDE combustor model can realize energy conversion in rotating detonation. The fuel-based specific impulse can reach around 7000 s. By comparing the results of hollow and annular combustors, some important differences are observed though general behaviors in these two RDE combustor models are similar. One is that there is no repeated reflection of shock waves in the hollow model. Another is that in the center of the cylinder part of fresh gas rolls inward into the region $r < R_{inner}$ and here the RDE experiences some non-detonation burning. Also, through the comparison and analysis, roles of the outer and inner walls are presented. Without the restriction of the inner wall, burnt gas flows a little more divergently.

1. Introduction

Combustion can be divided into two categories: deflagration and detonation. Combustion in conventional engines, such as piston engines and gas turbine engines, belongs to deflagration. The possibility of improving the efficiency by detonation instead of deflagration was first proposed by Zel'dovich [1]. The detonation cycle has a close thermal efficiency to that of the isochoric cycle. It could be 20% higher than that of conventional isobaric combustion, which is particularly attractive for aerospace propulsion. Furthermore, in contrast to meters per second propagation velocity of a deflagration wave, it is several thousand meters per second of a detonation wave. Thus detonation allows more intense and faster heat release, which means that enormous thrust can be created in a relatively small combustor. Therefore, using detonation in engines would be very efficient, and many efforts have been done on developing detonation engines.

One way to generate thrust utilizing detonation waves is to use the pulse detonation engine (PDE). It was firstly suggested by Nicholls et al. [2] in 1957. They built the first PDE, which utilized detonation of a hydrogen–air mixture to produce thrust. Later, numerous studies have been focused on it around the world. In a PDE, fuel is combusted via detonation by repeated and high-frequency ignitions. As its name suggests, a PDE relies on detonation to realize energy conversion. However, we need to achieve both the right frequency and high ignition energy for this type of engines to be practically used [3]. Besides, since most part of the operating processes does not produce thrust, it seems there exists a limitation on achieving high efficiency as desired.

The rotating detonation engine (RDE), which is also named continuous detonation engine (CDE) or continuously rotating detonation engine (CRDE) in some literatures, provides an alternative way for detonation propulsion. The fuel for an RDE is continuously fed axially through holes or slits in the head wall. One or several rotating detonation waves propagate circumferentially attached the head wall of the combustor. RDEs can continuously work without the whole processes in PDEs, which implies a great potential arising from their simplicity of design and manufacture, lack of moving parts, high thermodynamic efficiency and high energy conversion rate that may make them superior to PDEs.

The basic concept behind an RDE has been introduced by Voitsekhovskii et al. [4] in 1959. In recent years, many studies have

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been done on RDEs, bringing them closer and closer to practical application. A series of experiments by Bykovskii et al. [5,6] achieved both liquid and gas fuels continuous detonation with injection flows at different speeds and with different combustor shapes. Kindracki and Wolanski [7] experimentally produced continuously rotating detonation waves for about 0.8 s, including thousands of rounds inside the annular chamber. Significant propulsive performance was also measured in their experiments. RDE experiments have been carried out in several laboratories, such as Lavrentyev Institute of Hydrodynamics, Warsaw University of Technology, ENSMA and MBDA, AFRL, Pratt and Whitney, Aerojet, University of Texas at Arlington, Ohio State University, and Peking University [7–15]. Predominately hydrogen and methane were used as fuel. Other fuels like acetylene, ethane, propane, butane and even coal were also used in their tests.

Besides experimental researches, numerical simulations are always necessary to reveal the flow field and physical or chemical mechanisms in an RDE because of the high detonation velocity and the difficulties in 3D visualization. Initially, in many papers, like [16,17], the general structure of the rotating detonation was calculated. Later, more detailed calculations of the structure were performed. Zhdan et al. [18] did a wave structure analysis on a two-dimensional (2D) domain combining theoretical and numerical methods. Davidenko et al. [19] performed 2D numerical simulations using a high-resolution Euler solver and a reaction model with 6 species and 7 reactions and gave a parametric study to investigate the effect of the injection parameters, combustion chamber length, and spacing between successive detonation fronts on the integral characteristics of the combustion chamber operation. Hishida et al. [20] did a 2D numerical simulation and resolved the cellular structure of the detonation front and the Kelvin–Helmholtz (K–H) vortex behind the detonation front. Hayashi et al. [21] simulated K–H instabilities within an RDE in more detail. Since the detailed chemical reaction models were used in the above works, only a small 2D domain with a size of several millimeters can be treated. Shao et al. [22] performed 3D numerical simulation of RDEs by using cylindrical coordinates and two steps chemical reaction model, providing the propulsion performance. Yi and co-workers [23] also numerically investigated the propulsive performance of RDEs with various engine design parameters, including injection conditions, axial chamber length, and the number of detonation waves. Schwer and Kailasanath [24,25] examined the role of inlet stagnation pressure and back pressure and found that the height of the detonation wave and the mass flow rate were determined primarily by the stagnation pressure, whereas overall performance was closely tied to pressure ratio. Later they investigated the effect of adding an exhaust plenum to the RDE simulation in [26]. Zhou et al. [27] two-dimensionally investigated flow particle paths and thermodynamic performance of RDEs. To validate the possibility to place an rotating-detonation chamber (RDC) between the compressor and the turbine in an advanced gas turbine installation, Frolov et al. [28] performed a 3D numerical simulation of the operation of the RDC in order to determine the conditions of existence of detonation in the RDC, the thermal state of the chamber walls, and the most important parameters of the flow at the inlet and outlet of the RDC. Nowadays there are more and more research focused on RDEs. Nevertheless, in contrast to PDE studies, RDE studies are still at a preliminary stage. Physical mechanisms, detailed flow structures, performance analysis and numerical simulations of various initial and boundary conditions are all still needed.

So far, all RDE studies are based on the co-axial annular combustor model. Although studies of such a chamber configuration show that it works well for rotating detonation, it still needs further investigation and improvement to become a real engine. A major challenge related to the high power density and compactness of an RDE is the heating [12], and the ablation of the inner cylinder, which may need a complicated cooling system. In this paper, we propose an alternative model of RDE combustors, which we call the hollow combustor. In contrast to the co-axial annular combustor, a hollow combustor has no inner wall. It only has a cylindrical outer wall to keep rotating detonation waves inside the chamber. This could greatly reduce the difficulties in engine cooling. In order to validate if the rotating detonation waves could propagate in a hollow combustion chamber as well as in a co-axial annular combustor, we did a series of 3D numerical simulations, and investigated the features of them.

This paper is organized as follows. Section 2 describes the hollow combustor model, numerical methods and settings in the simulation. Section 3 discusses results, including whether the hollow combustor works for an RDE, how the detonation waves keep rotating, how the detonation waves come to stable propagation and the differences and similarities between the hollow and annular models. Before the conclusions in Section 4, we discuss their propulsive performances.

2. Physical model and numerical method

2.1. Hollow model

Figure 1(a) shows a typical schematic of the annular combustor model, on which many studies of RDEs have been done. Reactants are fed either separately or after being mixed into an annular combustor from the head end. A detonation wave or possibly multiple detonation waves rotate in the annulus attached to the head end, consuming the reactants which are continuously injected into the combustor. Due to the expansion effect behind the detonation front, its high pressure is then reduced to the level allowing the reactants to feed in again, by which the detonation wave could be self-sustaining.

Figure 1(b) shows the configuration we propose for the new model, the hollow combustor. Just as in the former model, the fresh gas (in this work a hydrogen–air mixture) is continuously fed into the combustor through small slits or holes in the head end and one or several rotating detonation waves propagate circumferentially consuming the reactants. The difference is that in the present

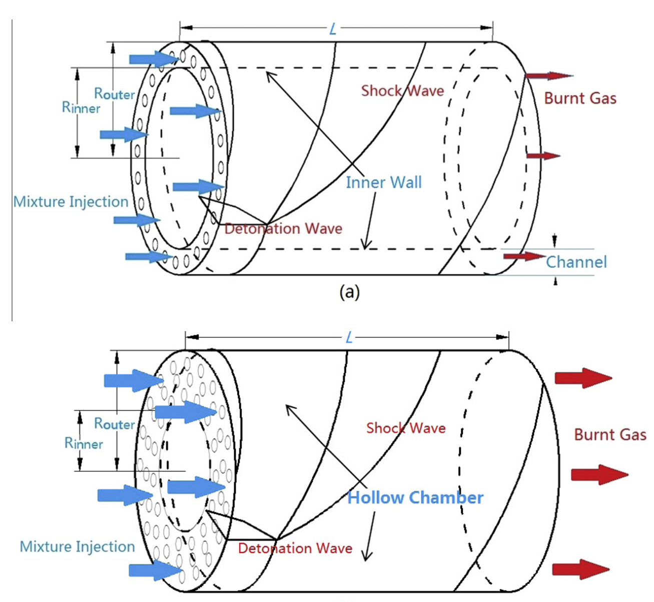

Fig. 1. Schematic of two models of the RDE combustor. (a) Annular model and (b) hollow model.