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Numerical investigations of the restabilization of hydrogen–air rotating detonation engines

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ABSTRACT

Based on 3D numerical simulations, the restabilization of hydrogen–air rotating detonation engines (RDEs) from one stable state to another after the operating conditions are changed is investigated. After a sudden change is imposed on the injection stagnation pressure, the transition process is clarified and the transition time, needed by the RDE to stabilize at a new state, is calculated. It is found that the sudden change of the stagnation pressure has an immediate influence on the average axial velocity at the head end of the RDE, which increases abruptly and instantly with the sudden rise of the stagnation pressure. After that, the average axial velocity drops and the average pressure increases gradually at the head end until they reach a new stable state. The average pressure has a bounce and the average axial velocity fluctuates at the head end in the transition process of the sudden decrease of the stagnation pressure. The total transition time increases with the variation range of the stagnation pressure. However, the initial adjusting time is independent of the variation range of the stagnation pressure and it is about twice the cycle period of the detonation wave around the chamber, demonstrating the high stability of the RDE.

Introduction

Detonation is an extremely efficient combustion process. Compared with conventional combustion, detonation allows more intense, more thermodynamically beneficial, and more stable burning of various fuels in smaller chambers. Thus, detonation waves have been explored extensively for propulsion applications because of their inherent advantages [1].

Among all the detonation engines, rotating detonation engines (RDEs) have received increasing attention in recent years. A typical RDE consists of one or more detonation waves rotating azimuthally around an annular chamber. Usually, the RDE is operated at a very high frequency. As long as a fuel-oxidizer mixture is supplied, it can work continuously and produce a roughly constant thrust with only a single initiation.

The concept of the RDE was first proposed by Voitsekhovskii [2] and a brief continuous detonation was obtained.

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Theoretical analyses and preliminary experimental research of the possibility of the application of rotating detonations to rocket propulsion were first conducted by Nicholls et al. [3] and Adamson et al. [4]. The feasibility of the RDE was first studied and shown by Bykovskii et al. [5] at the Lavrentyev Institute of Hydrodynamics. Presently, experimental research, numerical simulation and theoretical analysis of the RDE are carried out in many countries, including Russia [5,6], Poland [7], France [8], Japan [9,10], the USA [11,12], China [13–16] and so on. A detailed review of the development of the RDE was given by Wolanski [17].

According to the theoretical analysis by Fujiwara et al. [9] and the numerical investigation by Shao et al. [18], detonation waves in the RDE could stabilize for a wide range of the fuel-injection velocity (for both subsonic and supersonic injection). The experimental studies also showed that the RDE could be operated for a wide variety of fuels and injection conditions [5,7]. These efforts demonstrated the wide operating range of the RDE. The flow field dynamics of stable rotating detonation waves, which are established after ignition under invariant operating conditions, have been extensively explored.

When the operating conditions were changed, unstable propagating processes of detonation waves were observed in the previous experiments [7,12]. Furthermore, the RDE needs to be in different running states, namely, it should be able to adjust its working conditions timely to meet different flight missions for practical propulsion devices. Thus, the restabilization of the RDE from one stable state to another is an important issue that needs to be investigated in detail. So far, little has been done on this aspect of the RDE.

In present work, the restabilization of the RDE is investigated numerically. A stoichiometric hydrogen–air mixture is used as the reactants. To reveal the physical mechanism of the RDE more accurately, 3D simulations are carried out. Based on the evolution of detonation waves, the transition processes are analyzed after sudden changes are imposed on the injection stagnation pressure of a stable RDE. The transition time, needed by the RDE to stabilize at a new state, is calculated. Through this investigation, the propagating process of the detonation waves is better understood and the high stability of the RDE is proved numerically.

Physical model and numerical method

Physical model

Fig. 1 shows a basic combustion chamber of the RDE. The combustion chamber is a coaxial cylinder. The inner radius is 40 mm, the outer radius 50 mm, and the length 80 mm. For the ignition condition, the front section of the combustion chamber is initially filled with a premixed stoichiometric hydrogen–air mixture at a pressure of 1 atm and temperature of 300 K. The downstream area is filled with combustion products. A section of typical 1D detonation wave is placed at the head end region to initiate the 3D detonation, as shown in Fig. 1.

At the head end, a number of micro nozzles are distributed uniformly to inject the premixed stoichiometric hydrogen–air mixture into the chamber axially. In the simulation, the

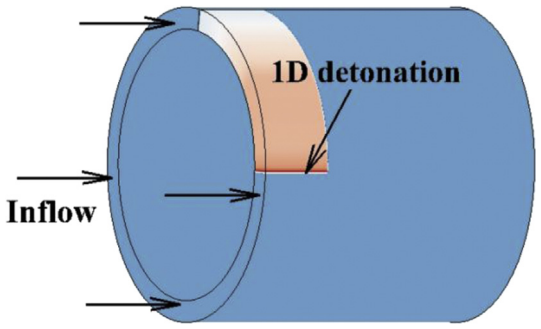

Fig. 1 – Computational domain for 3D simulation.

injection stagnation pressure and temperature (p_0 and T_0) of the reactants are set at constant values. The inflow from each nozzle varies considerably depending on the local pressure at the head end. The injection conditions are computed assuming isentropic expansion through the nozzles into the combustion chamber. The detailed description of the mixture injection boundary is in Ref. [13]. The environment pressure p_∞ is set to 0.5 atm. At the exit, non-reflecting outlet boundary conditions are used. A rigid wall condition is used on the inner and outer walls. The above boundary conditions are used extensively in current RDE numerical simulations.

Numerical method

As the main characteristics of shock waves (such as the shape, strength and propagating velocity) are usually not affected by viscous effects, like most existing numerical studies of shock and detonation waves [19–23], Euler equations with source terms due to chemical reactions are used in this paper. As a common reaction model, a one-step chemical reaction model [24] is used to describe stoichiometric hydrogen/air reaction. The justification of this reaction model is that only gas dynamic properties are considered here. The 3D governing equations are expressed in the generalized body-fitted coordinates as

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{E}}{\partial \xi}+\frac{\partial \mathbf{F}}{\partial \eta}+\frac{\partial \mathbf{G}}{\partial \zeta}=\mathbf{S} \tag{1}$$

where the conservative variable vector $\mathbf{U}$, the convective flux vectors $\mathbf{E}$, $\mathbf{F}$, and $\mathbf{G}$, and the source vector $\mathbf{S}$ are, respectively, defined as

$$\mathbf{U}=\frac{1}{J}\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ e\\ \rho\beta_1\end{pmatrix},\quad \mathbf{E}=\begin{pmatrix}\rho\overline{U}\\ \rho\overline{U}u+p\xi_x\\ \rho\overline{U}v+p\xi_y\\ \rho\overline{U}w+p\xi_z\\ \overline{U}(p+e)\\ \rho\overline{U}\beta_1\end{pmatrix},\quad \mathbf{F}=\begin{pmatrix}\rho\overline{V}\\ \rho\overline{V}u+p\eta_x\\ \rho\overline{V}v+p\eta_y\\ \rho\overline{V}w+p\eta_z\\ \overline{V}(p+e)\\ \rho\overline{V}\beta_1\end{pmatrix},\quad \mathbf{G}=\begin{pmatrix}\rho\overline{W}\\ \rho\overline{W}u+p\zeta_x\\ \rho\overline{W}v+p\zeta_y\\ \rho\overline{W}w+p\zeta_z\\ \overline{W}(p+e)\\ \rho\overline{W}\beta_1\end{pmatrix},\quad \mathbf{S}=\frac{1}{J}\begin{pmatrix}0\\0\\0\\0\\0\\ \rho\dot{\omega}_{\beta_1}\end{pmatrix}$$

$$\overline{U}=u\xi_x+v\xi_y+w\xi_z,\quad \overline{V}=u\eta_x+v\eta_y+w\eta_z,\quad \overline{W}=u\zeta_x+v\zeta_y+w\zeta_z$$

J is the Jacobian matrix and β_1 the reactant mass fraction.