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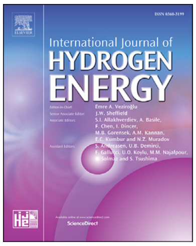

Propagation process of H_2/air rotating detonation wave and influence factors in plane-radial structure

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ABSTRACT

The rotating detonation wave (RDW) propagation processes and influence factors are simulated in the plane-radial structure. The effects of inner radii of curvature, domain widths and stagnation pressures on propagation mode are studied. The RDW is initiated, and two kinds of propagation mode are obtained and analyzed. The flow field structure, parameters variation and influence factors on unstable propagation mode are explored in depth, and the geometrical and injection conditions of the unstable propagation are obtained. Results indicate that the decoupling and re-initiation occur repeatedly during the unstable propagation mode of the RDW, and the angular velocities of leading shock wave vary accordingly. When the domain width remains constant, the range of stagnation-pressure under unstable propagation mode increases as the inner radius increases. But the RDW propagates steadily when the inner radius increases to a certain value (Larger than 40 mm in this study). The effect of curvature radius and initial pressure ahead of detonation wave on the unstable propagation mode in this calculation model is similar to that in a curved channel. When $r_i + 0.464p_a > 80.932$ or $r_i \geq 40$ mm, the detonation wave can propagate steadily in the annular domain. When the curvature radius remains constant, the stagnation-pressure range of the unstable propagation mode decreases as the domain width increases.

Introduction

Detonation combustion has the characteristics of high energy-release rate, thermodynamic efficiency and is closed to isochoric cycle. Based on the detonation combustion, Rotating Detonation Engine (RDE) is a new power propulsion engine in which one or more Rotating Detonation Waves (RDWs) propagate continuously for generating the continuous thrust. The RDE structure can be divided into three main types: coaxial annular cylindrical structure, hollow cylindrical structure without inner wall, and the plane-radial structure. Many experimental and numerical studies on the RDE have been investigated in recent years [1].

In experimental research, various gaseous and liquid fuel and oxidiser were used in the annular cylindrical combustor, and varied propagation modes of the RDWs were obtained [2,3]. Anand [4–6] et al. investigated the propagation processes of the RDW under different injection conditions and varied geometries, and revealed four instabilities. The propagation

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characteristics of the RDW in hollow combustor were studied, and varied combustion patterns were obtained [7–9]. The propagation mechanism and high frequency combustion instabilities of the RDW in hollow combustor were analyzed [10]. The experimental research of detonation-wave operating in an optically accessible non-premixed RDE is visualized using OH* chemiluminescence imaging [11], and the detonation-wave structure was observed. In numerical research, a detailed detonation-wave structure was obtained, and the detonation-wave characteristic of "a detonation-shock combined wave" was revealed [12]. The 2D and 3D detonation-wave structures were simulated and the impact factors of flow-field features and propagation processes of the RDW were researched [13–16]. The 3D numerical works were also operated in a hollow chamber, and the steady multi-wave rotating detonation was acquired [17,18].

Bykovskii [19–22] et al. designed the plane-radial detonation combustor for coal-air detonation experiments. The experiments initiated successfully and obtained the pulsed detonation wave and the RDW. The quartz-glass walls were applied in a plane-radial combustor to visualize the whole flow field of the RDW. Using the high speed camera and Schlieren instrument, the propagation process of the RDWs and flow-field structure were obtained [23,24]. Higashi [25,26] et al. designed a plane-radial rotating detonation turbine engine and performed the cold flow experiments and combustion experiments.

In addition, researchers also conducted some experimental and numerical studies on propagation mode of detonation wave in curved channels. Nakayama [27–29] et al. experimentally studied the detonation propagation phenomena in rectangular-cross-section curved channels. The effects of inner radii of curvature and filling pressures on the propagation modes of detonation wave were researched. Lee [30] et al. studied the effect of curvature on the detonation-wave propagation characteristics and cell structures in annular channels. Result showed that, the flow compression effect on the detonation propagation got stronger as the normalized radius became smaller. Yuan [31] et al. conducted the numerical simulation of detonation propagation in 90-degree bent tubes. The effects of curvature radius and initial pressure on the detonation decoupling and restoration were explored in depth, and the critical conditions for propagation mode transition were obtained. Li [32] et al. investigated the propagation mechanism of steady cellular detonation in curved channels, and obtained two kinds of propagation modes: detonation failure and re-initiation mode and steady detonation propagation mode.

The two-dimensional (2D) plane-radial domain is a simplified model of the plane-radial detonation combustor, which cannot take into considering the flow turning effects at the exit of the combustor. This 2D plane-radial structure has a convergent domain, and the inlet area is larger than the exit area, which is different from the conventional RDE. Moreover, the boundary conditions in this 2D annular convergent domain are different from that in curved channels, and the premixed reactant gas is dynamic gas. All factors lead to the difference of the RDW propagation characteristics among 2D plane-radial structure, conventional RDE and curved channel, which is necessary to carry out the researches in this study. What's more, the plane-radial RDE has a good match with a centrifugal compressor and a radial flow turbine [25], which will be beneficial to the engineering application of the RDE in the future. Based on the 7 species and 8 steps chemical reaction mechanism of stoichiometric hydrogen-air mixture, the RDW propagation characteristics in 2D plane-radial structure are researched in this study. The effects of curvature radii, domain widths, and stagnation pressures on the propagation modes of the RDW are studied. Two typical detonation-wave propagation modes are obtained. The flow field structure, detonation parameters and influence factors under unstable propagation mode are analyzed in depth. The operating conditions for detonation-wave decoupling and re-initiation are explored. The numerical simulations in this study are meaningful to reveal the propagation characteristics and impact factors of the RDW in the plane-radial structure, which will have great references for experimental researches in the future.

Physical and numerical method

Governing equation and numerical method

To study the propagation characteristic of the RDW in plane-radial structure, a detailed chemical reaction model is investigated in the 2D simulation for Hydrogen-Air detonation. The following assumptions are made to simplify the problem: (1) the gas is assumed to be ideal, non-viscous, and non-heat-conducting, and all diffusive effects are neglected; (2) the external forces such as gravity are neglected.

On the basis of the assumptions, the 2D chemical non-equilibrium Euler equations applied together with the conservation of mass of 7 species (H_2, H, O_2, O, H_2O, OH, and N_2) and with 8 elementary reaction models [33]:

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}=\mathbf{S} \tag{1}$$

where ***U*** is a conservative vector; ***F*** and ***G*** are non-viscous convective terms; and ***S*** is the chemical reaction source term, respectively. Each term is shown in Eq. (2).

$$\mathbf{U}=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ E\\ \rho Y_i\end{pmatrix},\quad \mathbf{F}=\begin{pmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (E+p)u\\ \rho Y_i u\end{pmatrix},\quad \mathbf{G}=\begin{pmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (E+p)v\\ \rho Y_i v\end{pmatrix},\quad \mathbf{S}=\begin{pmatrix}0\\ 0\\ 0\\ 0\\ \omega_i\end{pmatrix} \tag{2}$$

where ρ is the density of gas mixture, Y_i ($i = 1, \ldots, N_s-1$) is the mass fraction of the *i* th species, N_s is the total number of species, *u* and *v* are velocities in the *x* and *y* directions, ω_i is the production rate of the *i* th species by chemical reaction, and *E* is total energy of gas mixture, respectively. The total energy is defined as: