Numerical Investigations on the Three-dimensional Flow Patterns of the Continuous Rotation Detonation

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1 Introduction

In recent years, investigations on the detonation engine have become popular in the propulsion field due to its higher combustion efficiency, less pollution and wider flying Mach number comparable with the traditional combustion engines. Currently, there are three conceptions [1] to implement the effective propulsion. The first one is Pulse Detonation Engine (PDE), in which the thrust is obtained through cyclic high-frequency pulse detonation. The second is Oblique Detonation Wave Engine (ODWE), in which the detonation wave is stationary in the chamber and the engine flight velocity should be higher than the reacting mixture detonation velocity. However, there are some inherent difficulties in above two kinds of engines, for example, high-frequency ignition and the terrible noise in PDE, steady hypersonic incoming flow and high startup velocity in ODWE etc. So far, both of them have met their own troubles. The third is Continuous Detonation Wave Engine (CDWE), in which the steady detonation wave revolves along the fuel injection end and the products are threw away from the detonation front for the effect of the centrifugal force and rarefaction wave to fill with the fresh fuel as shown in Figure 1. CDWE possesses comprehensively some merits of both the PDE and ODWE. Many pioneering investigations on CDWE were performed both experimentally [1-7] and numerically [8-10]. But the flow pattern of the CDWE is not yet fully understood, and most of the previous numerical investigations are two-dimensional. In this paper, three-dimensional Euler equations with 9 species 19 step reactions of the H2-AIR mixture are solved with high-resolution Roe scheme and MPI parallel computing, and the three-dimensional flow patterns of the Continuous Detonation Wave are discussed in detail.

2 Numerical Method

Assuming the viscous effect is negligible, the three-dimensional chemical non-equilibrium Euler equations in non-dimensional and generalized body-fitted coordinate system are presented as:

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

Where, $\mathbf{U}=(\rho_1,\ \ldots\ \rho_K,\ \rho u,\ \rho v,\ \rho w,\ E)^T$, $\mathbf{S}=(\dot{\omega},\ \ldots\ \dot{\omega}_K,\ 0,\ 0,\ 0,\ 0)^T$

$$\mathbf{F}=\left(\rho_1\overline{U},\ \ldots\ \rho_K\overline{U},\ \rho u\overline{U}+p\xi_x,\ \rho v\overline{U}+p\xi_y,\ \rho w\overline{U}+p\xi_z,\ \overline{U}(p+E)\right)^T,$$

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$$\mathbf{G}=\left(\rho_1\overline{V},\quad ...\quad \rho_K\overline{V},\quad \rho u\overline{V}+p\eta_x,\quad \rho v\overline{V}+p\eta_y,\quad \rho w\overline{V}+p\eta_z,\quad \overline{V}(p+E)\right)^T,$$

$$\mathbf{H}=\left(\rho_1\overline{W},\quad ...\quad \rho_K\overline{W},\quad \rho u\overline{W}+p\zeta_x,\quad \rho v\overline{W}+p\zeta_y,\quad \rho w\overline{W}+p\zeta_z,\quad \overline{W}(p+E)\right)^T.$$

The components of the velocity in the computational coordination in ξ, η *and* ζ directions are $\overline{U}=u\xi_x+v\xi_y+w\xi_z$, $\overline{V}=u\eta_x+v\eta_y+w\eta_z$, $\overline{W}=u\zeta_x+v\zeta_y+w\zeta_z$. Here, *p*, ρ, *E* are the pressure, density and total energy per volume, respectively. ρ_k and Y_k denote the density and mass fraction of the species *k*, respectively. $\dot{\omega}_k$ is the mass production rate of species *k*,

$$\dot{\omega}_k=\sum_{i=1}^{I}\left(\gamma_{ki}^{''}-\gamma_{ki}^{'}\right)\left(k_{fi}\prod_{k=1}^{K}\left[X_k\right]^{\gamma_{ki}^{'}}-k_{bi}\prod_{k=1}^{K}\left[X_k\right]^{\gamma_{ki}^{''}}\right) \tag{2}$$

Where, X_k is the molar concentration of species *k*. The indices *i* and *k* denote the number of species and number of reactions, respectively. $\gamma_{ki}^{''}$ and $\gamma_{ki}^{'}$ denote the stoichiometric coefficients for the reactants and products, respectively. The forward rate constant k_{fi} and backward k_{bi} are obtained from Arrhenius law. The equation (1) indicates two processes, i.e. fluid dynamics and chemical reaction. With the time-operator splitting [11], the former is the homogeneous partial differential equation solved by using high-resolution Roe scheme[12], the later is the ordinary differential equation solved by using the LSODE package[13]. And the two-step Runge-Kutta method is performed on the time term.

Fig.1 is the schematic of the physical domain (the left) and its corresponding computational domain (the right). The annular combustion chamber [1] of the Continuous Rotation Detonation is closed on the upper end A (the end with fuel air mixture injected) and opened at the other bottom end (the end with products ejected) as shown in the left. Its inner (B) and outer(C) walls are circle cylindrical surfaces with diameter $1.4L_0$ and $1.8L_0$, respectively, and its height is $2.0L_0$. The deep gray color annular domain along the inner wall and adjoining to the closed end A in Fig.1 is filled with stoichiometric H2-AIR mixture, and other volume is filled with air. Its inner and outer wall diameter is $1.4L_0$ and $1.6L_0$, respectively and its height is $0.1L_0$. The chamber inner(B), outer(C) and closed end(A) wall is assumed to be the slip solid boundary, while the outflow condition is applied to the open (bottom) ends, and the periodic boundary is applied to the left and right sides of ignition plane in Fig.1. The initial condition is assumed that the temperature, pressure and density of the ignition domain are $T_{\text{ignition}} = 5.0T_0$, $P_{\text{ignition}} = 10.0P_0$, $\rho_{\text{ignition}} = 1.0\rho_0$, while the other are T_0, P_0, ρ_0 (standard condition) .

In the present calculation, the 9 species and 19 elementary reactions mechanism [10] was used to model the H2-AIR chemistry. The domain decomposition method was adopted for parellel computing with MPICH2, the total grid number is $\xi\times\eta\times\zeta = 60\times800\times200$. It costs 4 days with 32 subdomains to 32 CPUs (Quad-Core intel Xeon 2.33GHZ) of the PC cluster.

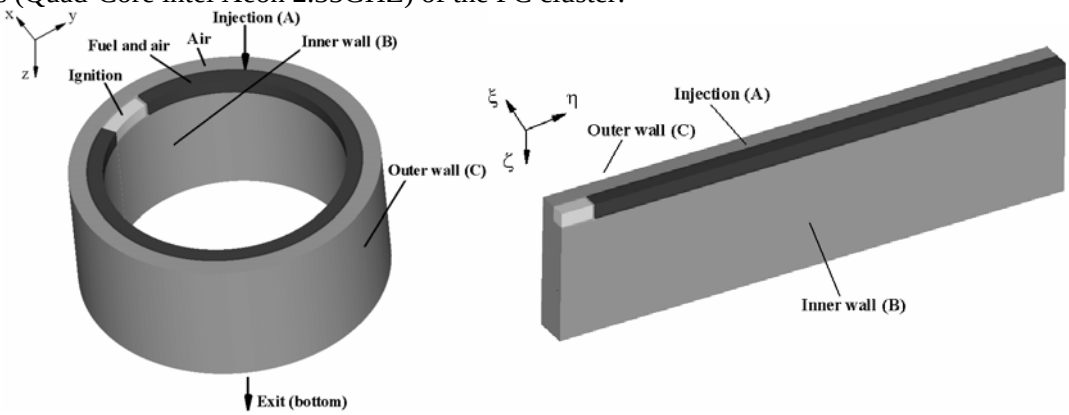
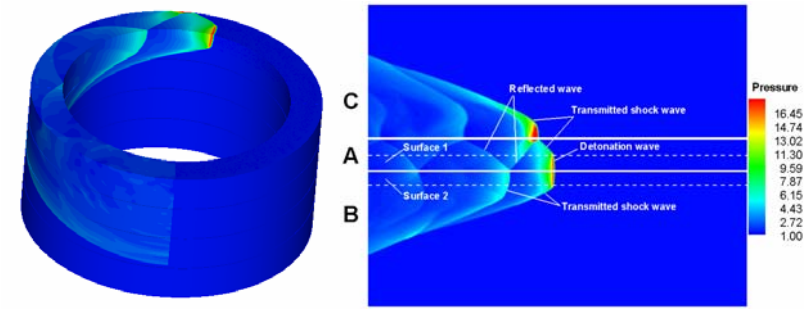


Figure 1 Schematic of computational domain.Left: pysical domain. Right: Computational domain

3 Results and discussions

Fig.2.a shows the three-dimensional structure of the CDWE combustor flow at t=0.50, where the detonation wave only appears in the inner fuel domain and propagates in the clockwise direction. Fig.2b gives the distribution of the pressure contours in three sides (A,B,C). The dashed lines indicate the interface between the mixture and the air. And the surface 1-2 in the section A and B is filled with the combustible mixture while the others are air. Detonation wave converts to the transmitted shock wave when it separate from surface 1 and 2 into air. The transmitted shock wave reflects repeatedly from the walls and attenuates gradually to the sound wave. In the outer wall section (C), it is all filled with air, and only have the reflection of the transmitted shock waves.



(a) Three-dimensional structure (b) Plane structure

Fig.2 Distribution of the pressure at t=0.50

Fig.3-4 indicate the distributions of the mass fraction of H2O and the temperature at t=0.50, respectively. With the effect of the transmitted shock wave and the centrifugal force, the detonation products expand outward and invade the space filled originally with air (Fig.3). It is obvious that temperature of the detonation products is higher than the area with fresh mixture and air (Fig.4).

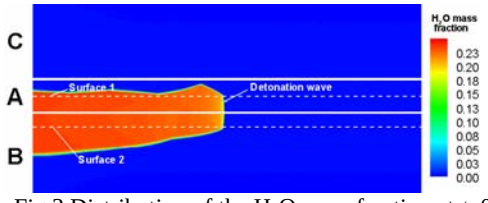


Fig.3 Distribution of the H_2O mass fraction at t=0.50

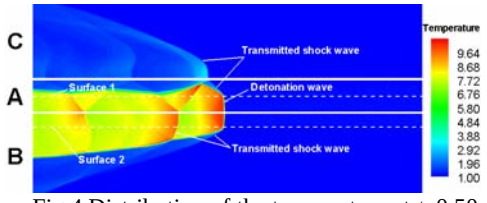
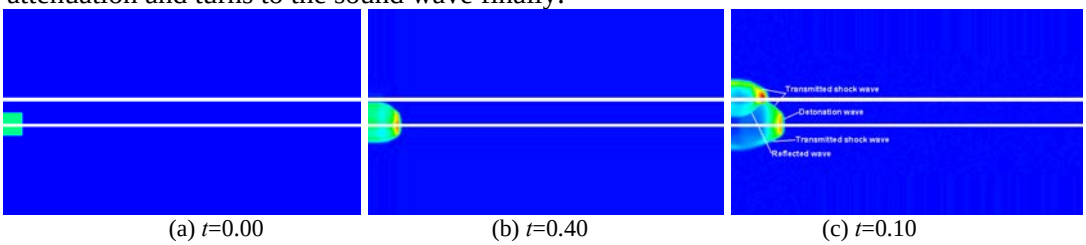
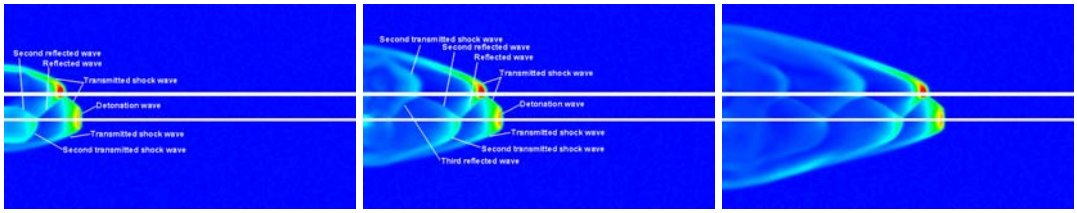


Fig.4 Distribution of the temperature at t=0.50

The pressure distribution at the different time is shown in Fig.5. With the effect of high temperature and high pressure the combustion rapidly translates into detonation (Fig.5b). The detonation wave penetrates the interface between the fresh mixture and the air and is converted to the transmitted shock wave which will reflect from the outer wall(C), as shown in Fig.5c. The reflected shock wave from the inlet section (A) will reflect from the inner wall (B) again, and forms the second reflected shock wave. And the second transmitted shock wave appears in the inner wall, as shown in Fig.5d. The second reflected shock wave reflects from the outer wall again and forms the third reflected shock wave. Simultaneously, the second transmitted shock wave appears in outer wall, as shown in Fig.5e. The above repetitive reflection process continues later (Fig.5e-5f), which makes the strength of the shock wave attenuation and turns to the sound wave finally.



(a) t=0.00 (b) t=0.40 (c) t=0.10



(d) t=0.15 (e) t=0.30 (f) t=0.50

Fig.5 Pressure distribution at the different time

4 Conclusions

In this paper, the three-dimensional flow patterns of the Continuous Rotation Detonation in CDWE are demonstrated based on our numerical results. Due to its complication, further experimental and more complicated numerical investigations have been performed to analyze its characteristics for practical applications.

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