Numerical Investigation of Continuous Detonation Engine

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1 Introduction

Detonation is an extremely efficient means of combustion. Taking advantages of nearly isochoric combustion process, detonation releases higher thermodynamic efficiency than conventional isobaric combustion. At 1atm and 273K, isochoric combustion of stoichiometric H2/O2 mixture has a 18%-37% enhancement of efficiency in comparison with isobaric combustion[1]. Furthermore, detonation allows more intense and steadier combustion which means just a smaller combustor that can create enormous thrust. All of these benefits make the research of detonation engine popular world widely. In the past two decades, significant efforts had been undertaken on research of the Pulse Detonation Engine (PDE). One can refer to Roy's paper [2] to review the research status of PDE.

Nevertheless, there are some hurdles that need to be overcome in PDE research, such as low operating frequency which means low mass flow and high ignition energy for each circle. Developing a detonation engine which can work without multi-ignition and whose fuel is injected continuously will greatly reduces the difficulties in design of aerospace thrusters of detonation combustion.

The concept of rotating detonation engine (RDE) was first proposed by Voitsekhoviskii[3, 4]. In contrast to PDE, the fuel of RDE is injected continuously into the detonation combustor through the holes or slits on the closed wall. The injection velocity can cover a large range from subsonic to supersonic. It requires only one time ignition, and then the detonation wave can propagate continuously in circumferential direction. Voitsekhoviskii experimentally achieved short-lived continuous detonation fueled by ethylene and acetylene respectively. RDE has been extensively studied in experimental way by Russian Lavrent'yev fluid research centre in the last thirty years [5-7]. The serial experiments which use the common aviation kerosene can achieve long time steady rotating detonation. However, there is always a need to study the flow field in detail by numerical methods. Recently, some numerical simulation [8-10] begins to deal with these problems. Fujiwara [9] firstly made a detail analysis of RDE, discovering a number of interesting physical phenomenons by two-dimensional numerical simulation. Hayashi's group[11, 12] did a series of numerical simulations on spin detonation's wave structure both in circular tube and co-axial cylinder, which are good references for RDE's flow structure analysis.

In contrast to PDE's comprehensive research, there is just a few two-dimensional numerical simulation on RDE. The previous RDE simulations are based on two- dimensional simulation via hypothesizing an infinite curve radius.

Apparently, there are some differences between them and the real physics model. Due to its attractive characteristics and great potential for aerospace thrust applicability, it is necessary to investigate more deeply and to understand what is going on in the tube. Detailed flow structure, RDE performance analysis and numerical simulation of various initial conditions have not yet been done. Instead of previous two-dimensional simulation, we carry out three-dimensional simulation on cylindrical coordinate system. This firstly lay out a three-dimensional flow field of RDE, ensuing a number of mechanism about RDE. Furthermore, we made a performance analysis based on our simulation.

2 Physical model

In this paper, the RDE physical model is a coaxial cylinder. Fig. 1 shows its propagation diagram. The gap between the two tubes is the combustor. The wall on the left is closed but drilled with a series of uniformly distributed small ports or slits to inject pre-pressed combustible mixture. Suppose that Stoichiometric H2/O2 mixture is uniformly injected into the combustor through the laval type ports, a little moment later after enough fuel has been injected, detonation is ignited directly at the head end. The detonation wave then will propagate around the circumferential direction periodically.

3 Numerical method

3.1 Governing equations

Two-step chemical reaction model is used to describe the H2/O2 reaction. The governing equations are the three-dimensional Euler equations on cylindrical coordinates:

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial r}+\frac{\partial F}{\partial \theta}+\frac{\partial G}{\partial z}+H=S$$

(1)

$$U=\begin{bmatrix}\rho \\ \rho u_r \\ \rho u_\theta \\ \rho u_z \\ e \\ \rho\beta \\ \rho\alpha\end{bmatrix},\quad E=\frac{1}{r}\begin{bmatrix}\rho u_r \\ \rho\left(u_r^2-u_\theta^2\right) \\ 2\rho u_r u_\theta \\ \rho u_r u_z \\ p u_r \\ \rho u_r\beta \\ \rho u_r\alpha\end{bmatrix},\quad F=\frac{1}{r}\begin{bmatrix}\rho u_\theta \\ \rho u_r u_\theta \\ \rho u_\theta^2+p \\ \rho u_\theta u_z \\ (e+p)u_\theta \\ \rho u_\theta\beta \\ \rho u_\theta\alpha\end{bmatrix}$$

$$G=\begin{bmatrix}\rho u_z \\ \rho u_r u_z \\ \rho u_\theta u_z \\ \rho u_z^2+p \\ (e+p)u_z \\ \rho u_z\beta \\ \rho u_z\alpha\end{bmatrix},\quad H=\frac{1}{r}\begin{bmatrix}\rho u_r \\ \rho\left(u_r^2-u_\theta^2\right) \\ 2\rho u_r u_\theta \\ \rho u_r u_z \\ p u_r \\ \rho u_r\beta \\ \rho u_r\alpha\end{bmatrix},\quad S=\begin{bmatrix}0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \rho\dot{\omega}_\beta \\ \rho\dot{\omega}_\alpha\end{bmatrix}$$

$p = \rho RT$

(2)

$$e=\frac{p}{\gamma-1}+\beta\rho q+\frac{1}{2}\rho u_r^{\,2}+\frac{1}{2}\rho u_\theta^{\,2}+\frac{1}{2}\rho u_z^{\,2}$$

(3)

$$\omega_\alpha=\frac{d\alpha}{dt}=-k_1\rho\exp(-E_1/RT)$$

(4)

$$\omega_\beta=\frac{d\beta}{dt}=\begin{cases}-k_2p^2[\beta^2\exp(\frac{-E_2}{RT})-(1-\beta)^2\exp(-\frac{E_2+q}{RT})]\ (\alpha=0)\\ 0 \qquad\qquad (0<\alpha<1)\end{cases} \qquad (5)$$

where ρ represents the density, u_r is the radial velocity, u_θ is the circumferential velocity, u_z is the axial velocity, p is the pressure, e is the total energy per volume, T is the temperature, γ is the specific heat ratio, q is the heat release of the chemical reaction, α is the reaction progress parameter in the induction period, β is the reaction progress parameter in the exothermic period, k_1 and k_2 are the rate constants, E_1 and E_2 are the activation energies, R is the gas constant, ω_α and ω_β are the reaction rates. In this paper, k_1, k_2, E_1 and E_2 are given as what Korobeinikov[13] gave, while γ and q are given as what Merkle gave[14]. Flux terms are solved by monotonicity preserving weighted essentially non-oscillatory (MPWENO)[15] scheme. Time integration takes the 3rd order TVD Runge-Kutta method. For two-dimensional simulation case, we consider radius is constant, and $\frac{\partial}{\partial r}=0$ in the governing equations.

3.2 Boundary and initial conditions

The mesh information and some boundary conditions are summarized in Table 1. Area of inject wall normalized by area of inject throat is Aw/Athroat=3.726. The head end boundary condition is specified according to the local wall pressure. According to the designed laval tube configuration, when wall pressure Pw<29.48atm, the throat keeps sonic velocity, and the the mass flux of injection ($\dot{m}=\rho u_z$) keeps constant.

When 29.48atm < P_w <30atm, the flux through both throat and injection wall is subsonic, while $\dot{m}$ drops down. When wall pressure is higher than stagnation pressure, i.e., P_w>30atm, the injection is stopped and its velocity equals to zero, a rigid wall condition is set locally. The above relations are showed explicitly in Fig. 3. The side wall boundary conditions are adiabatic, slipping, and noncatalytic. The downstream condition is nonreflection boundary[16]. To reduce the computing time, we equally extend a previous computed two-dimensional simulation flow field[17](Fig. 2) to three-dimensional combustor along radius direction at initial time. In Fig. 3, β =1 means fresh fuel mixture, β =0 means completely burnt gas.

Table 1: Initial condition

Inject stagnation pressure	30atm
*A*w /*A*throat	3.726
Biggest inject mach number	2.866
Inner radius	1cm
Outer radius	1.3cm
Combustor length	5cm
Total mesh number	30*600*500
Radius mesh size	$\Delta r = 0.1mm$
Circumferential mesh	$\Delta\theta = 2\pi/600$
Axial mesh size	$\Delta z = 0.1mm$

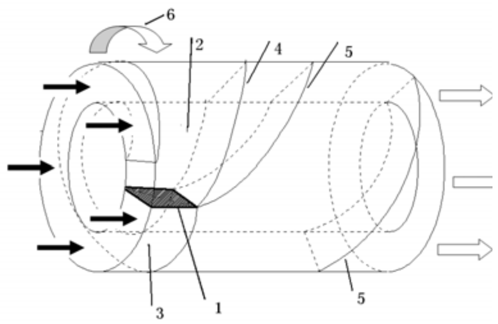

Fig. 1 RDE propagation schematic structure. 1-detonation wave, 2-burnt product, 3-fresh premixed gas, 4-slip line, 5-oblique shock wave, 6-detonation wave propagation direction.

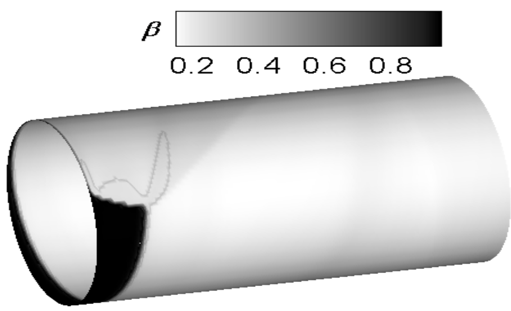

Fig. 2 Chemical reaction process parameter β distribution in two-dimensional simulations . β =1 means fresh fuel, β =0 mean completely combusted product.

4 Results and discussions

To achieve continuous detonation, it is required to consider the following key issues. First of all, we need to clearly understand the wave structure. Secondly, we should find out whether the injected fuel will be burnt out rapidly by deflagration other than detonation. And the third, the propulsion performance which is highly concerned in engine design should be studied. In the following sections we will discuss the above-mentioned issues.

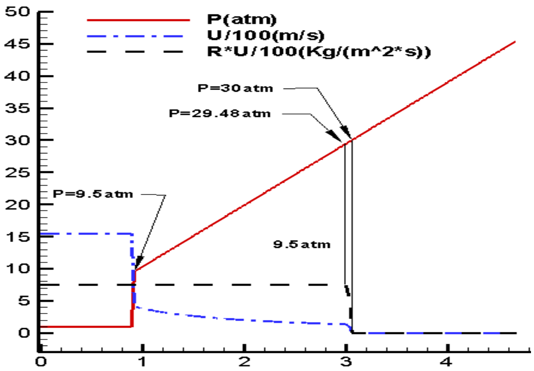

Fig. 3 Relationship between wall pressure、inject velocity and mass flux of injecting mixture.

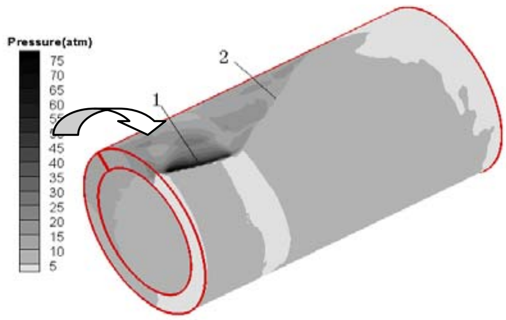

Fig. 4 Pressure distribution at 72 μs .1-detonation wave，2-oblique shock wave. The arrow indicates the detonation wave propagate direction.

4.1 flow field structure

First, we lay out an overview of the results. Figures 4 and 5 show the pressure and temperature distribution at 72 μs when the detonation wave has already propagated three circles and reached to a stable state. The fuel is injected from the left side, and the detonation products come out from the left side. The detonation front (indicated by number 1) is propagating in circumferential direction. It is not perpendicular to the wall but with a leaning angle. The oblique shock wave (indicated by number 2) sweeps the detonation products of the previous circle. A slip line of the product interface of the previous cycle and the present cycle can be seen clearly in Fig. 5. This structure maintains a stable flow field. It qualitatively agrees with the experimental result [5]. The stream lines are also showed in Fig. 5. The product runs circumferentially in the region just behind the detonation wave. After a series of expansion wave, the product mainly runs along the axial direction. We calculate the kinetic energy proportion of three directions by the following formulas:

$$
\begin{aligned}
U^2 &= \frac{1}{S_k}\int u^2{}_r(r,\theta,k)ds(r,\theta) \\
V^2 &= \frac{1}{S_k}\int u^2{}_\theta(r,\theta,k)ds(r,\theta) \\
W^2 &= \frac{1}{S_k}\int u^2{}_z(r,\theta,k)ds(r,\theta)
\end{aligned}
\tag{6}
$$

The proportion of each component is shown in Fig. 6. The axial kinetic energy occupies the leading role. The circumferential and angular kinetic energy which does not produce thrust take less proportion. We extract a one-dimensional line from Fig. 4 at r=1.15cm, z=0.3cm to study the pressure and temperature distribution along this line which are shown in Fig. 7. The typical detonation characteristic can be recognized by both the pressure and the temperature lines.

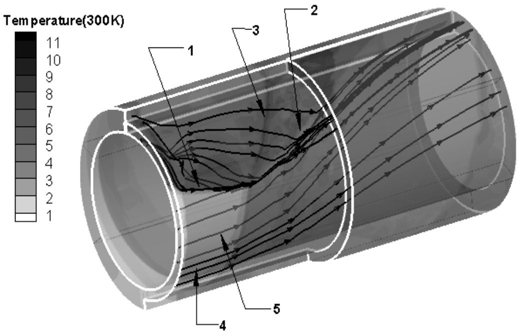

Fig. 5 Temperature distribution at 72 μs .1-detonation wave，2-oblique shock wave, 3-slip line，4-triangle zone of fresh premixed gas，5-stream lines

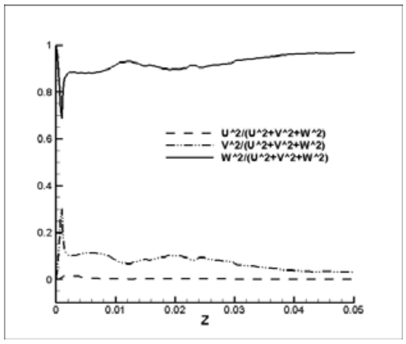

Fig. 6 Average kinetic energy proportion of cross section from head wall to exit plane at 72 μs .

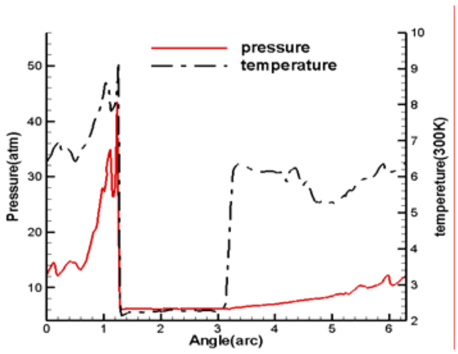

Fig. 7 Pressure and temperature distribution along a circle line at position r=1.15cm, z=0.2cm at 72 μs .

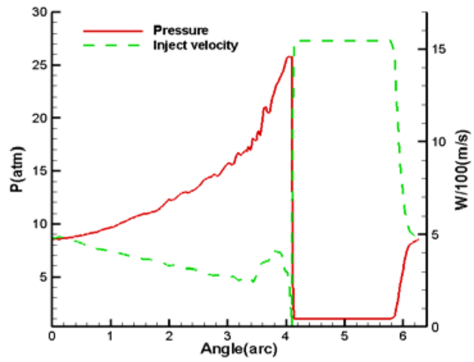

Fig. 8 Pressure and inject velocity distribution just near the head wall along a circle line which is at r=1.15cm,z=0 at 87 μs .

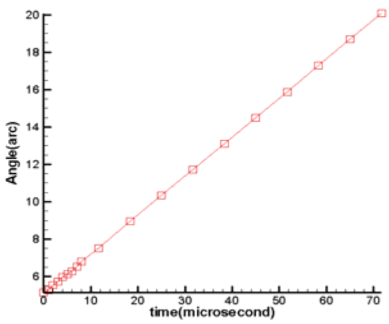

Fig. 9 Detonation wave front position from 0-72 μs .

4.2 Premixed gas injection problem

After the detonation swept over the pre-mixed gas in front of it, the pressure is very high following the wave. Fig. 8 shows the pressure and the injection velocity distribution just behind the head wall along a circle line. It is seen that the pressure rises steeply after the detonation wave, which leads to the injection velocity of premixed gas droping down. When the thrust wall pressure is greater than the inflow stagnation pressure by 30atm, the injection velocity becomes 0. The average wall pressure is about 9.52atm after becoming steady. In fact, the fresh fuel will be heated up by the hot wall which keeps nearly 2000K at head end in experiment [18].This will improve detonation combustion, and the present code does not consider this effect.

4.3 detonation wave velocity

Because the initial condition derives from a previous two-dimensional simulation result, the propagating velocity fluctuated at the initial 10 microseconds, and then it nearly keeps constant. According to Fig. 9, from 10-72 microseconds, the detonation wave velocity D=$r*\Delta\theta/\Delta t$=2711m/s. Unlike C-J theory model, in rotating detonation, the detonation product have one side likes a freedom interface, detonation wave speed at this situation will be discounted[19]. Experimental data also showed that the wave velocity was less than the C-J velocity[5].

4.4 pre-combustion problem

As the temperature of the detonation product is very high, it looks like that the injected fuel will be burnt out contemporarily. However, due to the propagating velocity between deflagration and detonation are at different levels, only a thin layer of fuel would be burnt out. Most of the injected fuel would be kept unburnt for next circle of detonation wave burnt. Therefore the detonation wave can keep propagating continuously. Fig. 10 shows the reaction progress parameter β distribution in the first cycle from 0-30 μs . When the flow field becomes stable, the fresh premixed gas occupies a dynamic triangle region. The detonation combustion and the premixed gas injection keeps a dynamic triangle zone.

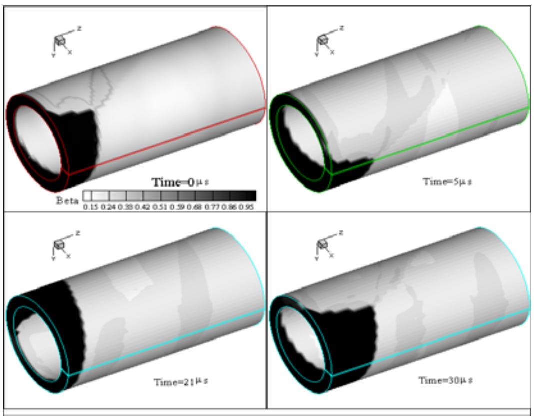

Fig. 10 Reaction progress parameter β distribution in one cycle form 0-30 μs .

4.5 Performance Analysis

Now, we compute some cases to study different parameters' effect on the flow field. In order to decrease the CPU time, we numerically simulate some two-dimensional cases to analyse the thermodynamic performance. To present the mass flow $\dot{m}$ and the specific impulse Isp at open end, we have formulas as:

$$\dot{m} = \frac{1}{S_k}\int \rho u_z(r,\theta) ds_k(r,\theta)$$

$$I_{sp} = \frac{\frac{1}{S_k}\int (\rho u_z^2(r,\theta) + P(r,\theta)) ds_k(r,\theta)}{\dot{m}}$$

where S_k is the area of open end, s_k is the area of each grid; detonation wave velocity is calculated using method such as the one described in section 3.2. Overall performance are summarized in table 3. It can be seen from the table, with the stagnation pressure increasing, the average mass flow, specific impulse have a linear growth. Because the tube length is so short that combustion products have not been fully expanded, a longer tube may create a bigger specific impulse. Three –dimensional numerical simulation obtained simular specific impulse with the two-dimensional simulation. We should further study the longer and thicker combustor case, and also have to calculate the nozzle's effect later.

5 Conclusion

This paper studies the rotating detonation engine in terms of flow field, burning mechanism, and performance efficiency. The feasibility of RDE was recognized by three-dimensional numerical simulation. The typical flow field structure was obtained and it agrees with the experiment. The simulation process can keep stable for long time, and the following collusions are obtained:

(1) The numerical simulation results of flow field structure agree well with previous experiment result, and we also show the typical detonation characteristics by illustrating the whole perform process qualitatively.

(2) The detonation product has high pressure. Due to the expansion wave's effect, wall the pressure is low enough to inject fuel in most areas of the inject.

(3)Because of the propagating velocities of a detonation and a deflagration wave are at different levels, only a thin layer of injected fuel would be burned out. And it is possible to inject enough fuel to maintain the detonation wave.

(4)With the stagnation pressure increasing, the average flow flux, specific impulse has a linear growth. The thrust performance computed from three-dimensional simulation results is similar with the two-dimensional simulation.

Table 2 Performance compute:

Compute Case	Dimension	Stagnation Pressure	Combustor Radius	Tube length	Specific Mass Flow （kg/(s.m^2)）	Isp(m/s)
case1	2D	10atm	1cm	5cm	237.29	2623
Case2	2D	15atm	1cm	5cm	365.56	2449
Case3	2D	20atm	1cm	5cm	495.13	2368
Case4	2D	25atm	1cm	5cm	632.02	2320
Case5	2D	30atm	1cm	5cm	765.40	2288

Case6	3D	30atm	R_{in}=1cm, R_{out}=1.3cm	5cm	754.20	2188

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