Numerical Simulation of the Rotating-Detonation Process with Nonpremixed Injection of Hydrogen and Air

Dong Li[1,2], Yining Zhang[2], Guozhu Liang[1], Jishuang Gong[2], Hao Meng[2]

1. School of Astronautics, Beihang University, Beijing 100083, China

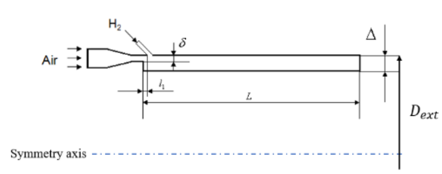
2. State Key Laboratory of Laser Propulsion and Aplication, Beijing Power Machinery Research Institute, Beijing 100074, China

1 Introduction

The rotating detonation engine (RDE) is an intriguing approach to achieving pressure gain combustion and higher thermal efficiency of circle for propulsion and power systems. A large amount of experimental studies [1-5] have fully proved the feasibility of RDE. As the process of rotating detonation combustion is unsteady, it's difficult to obtain the detailed wave structure in the combustor by experiment, numerical method is an indispensable means to study RDE. In this study we design a rotating-detonation combustor (RDC) and calculate the mixing process of the air and hydrogen, then simulate the operation of the RDC with hydrogen and air supply separately.

2 Rotating-Detonation Combustor Model

Figure 1 shows a diagram of the RDC. The model appears to be an axisymmetric annular channel with an internal and external diameters of the annular gap of $D_{ext} = 120mm$ and $D_{int} = 110mm$, respectively with gap width of $\Delta = 5$mm, and a length of $L = 70$mm. Air flows into the combustor through an annular slit of width $\delta = 2$mm in the axial direction. Hydrogen enters the annular channel through 80 square holes, which are evenly spaced over the circumference of the chamber's outer wall and $l_1 = 1mm$. The right end of the RDC is open to the environment.



Correspondence to: lgz@buaa.edu.cn

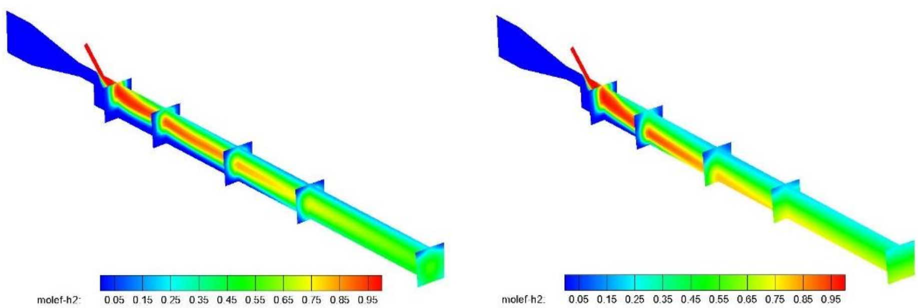
Figure 1. Rotating detonation combustor model

3 Numerical Methodology and Basic Parameters

This paper used Fluent solver based on the Navier-Stokes equation and the hydrogen-air finite chemical reaction rate model. The hydrogen-air mixture was modeled with 7 components (H2, O2, OH, H2O, H, O, N2) 8 steps Arrhenius kinetics. The implicit method is used to solve the equation and the turbulence model is the standard $k-\varepsilon$ model. The physical flux is discretized by AUSM method, convective and viscous term are discretized by the third-order MUSCL scheme, and time term is discretized by the second-order implicit scheme. The boundary conditions of air and hydrogen inlet are the pressure inlet, the total pressure of air inlet varies from 0.4atm to 0.8atm and the total pressure of hydrogen varies from 10atm to 15atm. The outlet boundary is pressure outlet.

4 Results and Discussion

From figure 2, as the injection holes are spaced over the outer wall, the hydrogen is rich near the outer wall region, as the axial distance increase the air and hydrogen mix gradually evenly. As shown in table 1, higher injection pressure of fuel leads to the increase of the hydrogen penetration depth and greater loss of the total pressure.



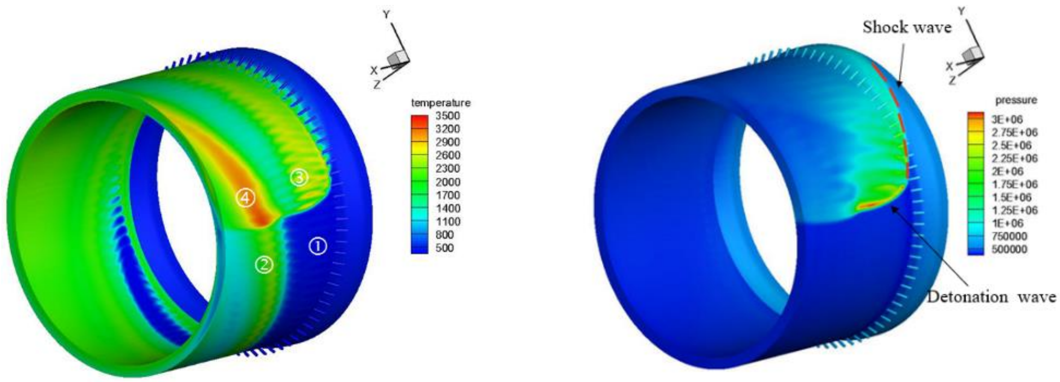
(a) Pt_f=10atm (b) Pt_f=15atm

Figure 2. Species fraction distribution of hydrogen at different injection pressures

Table 1: Total pressure losses at different axial distance

Pt_f(atm)	x=10mm	x=30mm	x=50mm	x=70mm
10	26.97%	36.54%	42.63%	45.03%
15	29.4%	41.06%	44.05%	49.25%

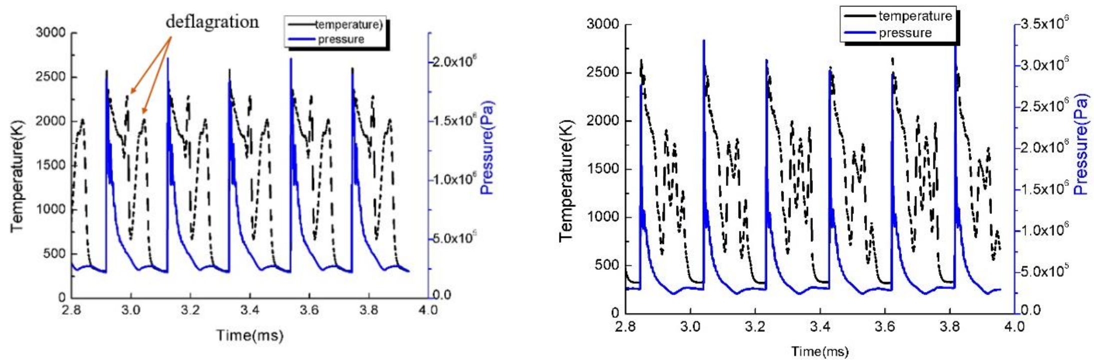
Two hydrogen injection conditions both provide a stable operation of the RDC with one detonation wave (DW), which becomes periodic about 3ms after initiation. Figure 3 shows the instantaneous distribution of temperature and pressure at t=4ms, the flow field is divided into four zones by detonation wave, oblique shock waves and contact discontinuity: zone one is the fresh air-hydrogen filled region , zone two is the product region of the previous detonation cycle, zone three is the product region of the new detonation cycle, zone four is the product region compressed by oblique shock waves.



(a) temperature (b) pressure

Figure 3. Instantaneous parameter distribution near the external wall of RDC

For a quantitative analysis of the reaction front, consider figure 4, which shows the change of the static pressure and static temperature over the time at a point (x=15mm, y=54mm, z=0mm), the pressure and temperature rise rapidly when the DW passes through the point, the pressure quickly decreases as the DC continues to move, but the contact deflagration results in slower temperature drop. As shown in table 2, higher injection pressure of fuel leads to higher peak pressure and peak temperature and faster velocity of the DW.



(a) Pt_f=10atm (b) Pt_f=15atm

Figure 4. Detonation parameter variations with time

Table 2 Detonation wave parameters at different injection pressures

Pt_f (atm)	Peak pressure (Pa)	Peak temperature (K)	Velocity (m/s)	Period (μs)
10	1952736	2586.6	1793.4	206.6
15	3051713	2604.0	1913.2	193.7

Figure 5 shows the change of the total pressure at different axial distance. As the injection pressure increases the total pressure along the distance increase and the RDC can be divided into three zones according to the change of total pressure: zone one is the air-hydrogen mix and deflagration region and total pressure decreases, zone two is the detonation combustion region and total pressure increases, zone three is the product expansion region and total pressure decreases.

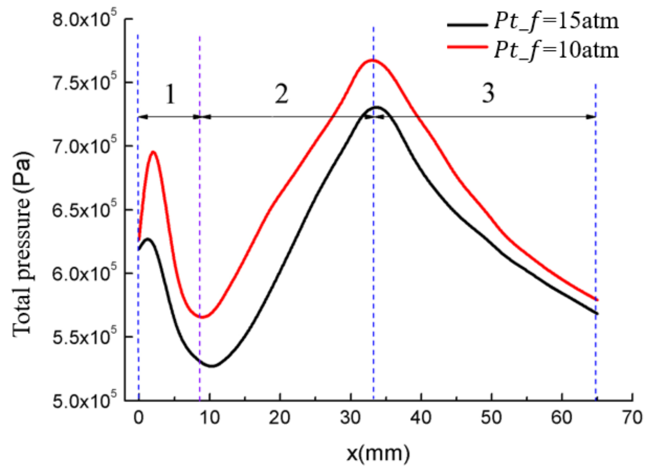


Figure 5. Comparison of the total pressure at different axial distance

5 Conclusion

We have successfully achieved a three-dimensional numerical simulation of the operation of an annular RDC with separate supply of hydrogen and air and compared the differences of RDC under different injection pressures. As the injection pressure of fuel increases, the peak pressure and peak temperature and velocity of the DC and the total pressure along the distance of RDC increase. More numerical simulation needs to be carried out to fully understand the RDE.

References

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