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Procedia Engineering 99 (2015) 848 – 852

Procedia Engineering

www.elsevier.com/locate/procedia

"APISAT2014", 2014 Asia-Pacific International Symposium on Aerospace Technology, APISAT2014

The Effect of the Inlet Total Pressure and the Number of Detonation Waves on Rotating Detonation Engines

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Abstract

This paper presented a three-dimensional numerical study of rotating detonation engines, exploring the effect of the inlet total pressure and the number of detonation waves on the performance of rotating detonation engines. It was found that under the same total pressure of the inlet fuel, the number of detonation waves had little influence on the specific impulse, the thrust and the outlet flow of RDE. The number of detonation waves, however, affected the time needed to reach stable detonation. Besides, there was instability phenomenon in the development of detonation waves due to the relation between the number of detonation waves and the inlet total pressure. In order to speed up the process from ignition to stable detonation, the total pressure of the inlet fuel should match with the ignitions.

Peer-review under responsibility of Chinese Society of Aeronautics and Astronautics (CSAA)

Keywords: numerical simulation; rotating detonation; multiple wave fronts

1. Introduction

The detonation engine is a new concept engine utilizing detonation as its primary method of combustion. Rotating detonation engines (RDE), as a type of promising detonation-driven engine, have aroused the interest of many researchers in recent years. Fundamental and early researches of RDE were investigated by Voitsekhovskii [1] and Nicholls et al. [2] Experimental researches have been done by Bykovskii [3], Wolanski et al. [4], and Wang et al. [5].

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Peer-review under responsibility of Chinese Society of Aeronautics and Astronautics (CSAA)
doi:10.1016/j.proeng.2014.12.611

Early two-dimensional numerical simulations of RDE were performed by Zhdan et al. [6] in an annular chamber with a hydrogen-oxygen mixture. Davidenko et al. [7], Schwer and Kailasanath [8], and Shao et al. [9] have also performed many numerical researches in RDE.

In the previous researches [10], there have been reported the multiple wave fronts phenomenon in RDE. However, there is not yet complete numerical study of this phenomenon. This paper used premixed hydrogen-air Arrhenius one-step chemistry model, exploring the effect of the number of detonation waves and the inlet total pressure on rotating detonation engines.

Nomenclature

P_0	inlet total pressure
T_s	stabilizing time
I_s	specific impulse
F_p	thrust
O_f	outlet flow
P	pressure
e	total energy
γ	heat ratio
R	gas constant
$\dot{\omega}$	mass production rate

2. Physical model and numerical method

The three-dimensional Euler equations with source term were used as governing equations, ignoring viscosity, thermal conduction and mass diffusion:

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

where the variables are

$$U=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ e\\ \rho Z_1\end{pmatrix}, S=\begin{bmatrix}0\\0\\0\\0\\0\\ \rho\dot{\omega}_1\end{bmatrix}, E=\begin{pmatrix}\rho_1\bar{U}\\ \rho\bar{U}u+p\xi_x\\ \rho\bar{U}v+p\xi_y\\ \rho\bar{U}w+p\xi_z\\ \bar{U}(p+e)\\ \rho\bar{U}Z_1\end{pmatrix} F=\begin{pmatrix}\rho\bar{V}\\ \rho\bar{V}u+p\eta_x\\ \rho\bar{V}v+p\eta_y\\ \rho\bar{V}w+p\eta_z\\ \bar{V}(p+e)\\ \rho\bar{V}Z_1\end{pmatrix}, G=\begin{pmatrix}\rho\bar{W}\\ \rho\bar{W}u+p\zeta_x\\ \rho\bar{W}v+p\zeta_y\\ \rho\bar{W}w+p\zeta_z\\ \bar{W}(p+e)\\ \rho\bar{W}Z_1\end{pmatrix}, \tag{2}$$

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

The pressure P and total energy e are calculated through the equation of state,

$$p=\rho RT, \tag{3}$$

$$e=\frac{p}{\gamma-1}+Z_1\rho q+\frac{1}{2}\rho u^2+\frac{1}{2}\rho v^2+\frac{1}{2}\rho w^2. \tag{4}$$

The specific heat ratio γ, gas constant R and mass production rate $\dot{w}$ are computed by the relation

$$R=\sum Z_i R_i, \tag{5}$$

$$\gamma = \frac{\sum Z_i R_i \gamma_i / (\gamma_i - 1)}{\sum Z_i R_i / (\gamma_i - 1)}, \tag{6}$$

$$\dot{\omega}_1 = \frac{dZ_1}{dt} = -AZ_1 \exp(-T_a / T). \tag{7}$$

where Z_1, Z_2, Z_3 are the mass fractions of gas mixture, combustion product and air, respectively.

We used fifth-order MPWENO scheme to split the flux vectors and third-order TVD Runge-Kutta method for time integration. The one-step chemistry model parameters are the same as those Ma et al. [11] used. Details of the numerical method and the grid analysis can be found in our previous study [9].The combustion chamber of the RDE was a coaxial cavity with a toroidal section shown in Fig. 1. The outer and inner radii were 6 cm and 5 cm respectively. The chamber length was 6 cm.

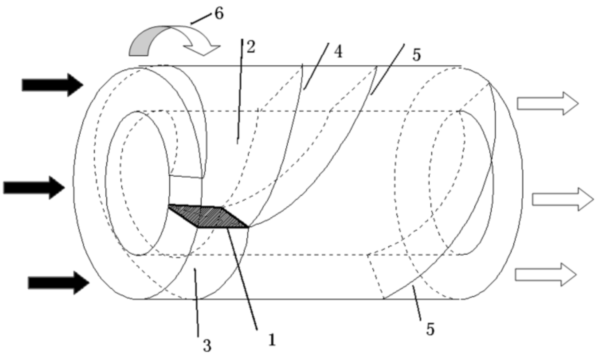

Fig. 1. Schematic plot of RDE. 1-detonation wave, 2-burnt product, 3-fresh premixed gas, 4-slip line, 5-oblique shock wave, 6-detonation wave propagation direction.

One-dimensional detonation waves were used in the headwall to initiate the detonation. To generate flow field with multiple wave fronts, one-dimensional detonation wave tubes were uniformly distributed in the headwall of the chamber for ignition, shown in Fig. 2.

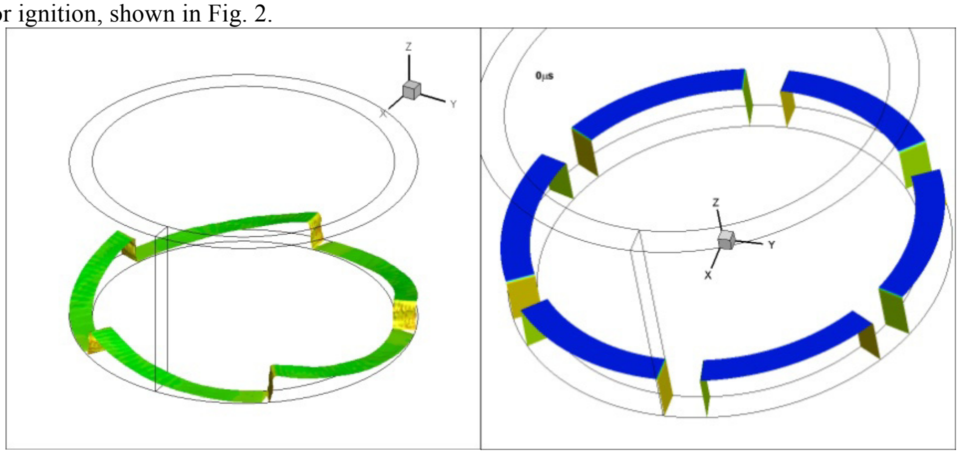

Fig. 2. The ignition setting on the headwall.

3. Results and discussion

Abundant fuel was needed for continuous propagation of detonation waves. The size of chambers and the injection setting both had effect on fuel injection. Here we focused on the fuel injection.

Table 1: Different cases under various total pressures

$P_0(atm)$	*Indicators*	*1-W*[1]	*2-W*	*3-W*	*4-W*	*5-W*	*6-W*
30	$T_s(\mu s)$	1200	730	540	480	500	560
	$I_s(s)$	5700	5780	5820	5800	5800	5780
	$F_p(N)$	1900	1990	2070	2100	2120	2100
	$O_f(kg/s)$	1.19	1.23	1.27	1.29	1.30	1.29
25	$T_s(\mu s)$	1400	500	600	490	630	
	$I_s(s)$	5530	5590	5630	5620	5620	
	$F_p(N)$	1500	1580	1640	1680	1680	
	$O_f(kg/s)$	0.98	1.01	1.04	1.06	1.07	
20	$T_s(\mu s)$	1200	490	580	560		
	$I_s(s)$	5190	5300	5340	5350		
	$F_p(N)$	1090	1170	1220	1680		
	$O_f(kg/s)$	0.76	0.79	0.82	1.06		
15	$T_s(\mu s)$		500	530			
	$I_s(s)$	5600	4850	4830			
	$F_p(N)$	860	800	820			
	$O_f(kg/s)$	0.55	0.59	0.58			
10	$T_s(\mu s)$		930				
	$I_s(s)$	3850	3930				
	$F_p(N)$	410	430				
	$O_f(kg/s)$	0.38	0.39				

[1] 1-W=one-wave. And so on.

Different numerical cases under various inlet total pressures were tested in our study. The following results presented the performance indicators of stabilizing time(T_s), specific impulse(I_s), thrust(F_p) and outlet flow(O_f) under various inlet total pressures(P_0), listed in Table 1.

Based on the simulations above, it was found that there was unstable combustion of detonation waves, shown in Fig. 3. In Fig. 3a, the detonation waves were shrinking due to lower inlet total pressure. The yellow areas were the detonation wave fronts which were about to combust the newly injected fuel mixture. If the size of the detonation waves was too small to maintain the propagating, the detonation waves would die out. Since the travel speed of the detonation waves remained constant, to ensure enough fuel injection, it was necessary to either cut down the number of ignition areas or increase the inlet total pressure. The lower inlet total pressure, however, was not the only reason for unstable combustion. In the course of detonation waves propagating, certain energy was needed to detonate the fuel gas in front. Therefore, if the chemical reaction of this part of fuel gas was not fast enough to produce adequate energy, the detonation waves would shrink. By enlarging the image, it could be seen in Fig. 3b that the unreacted air mass was desquamating behind the detonation wave.

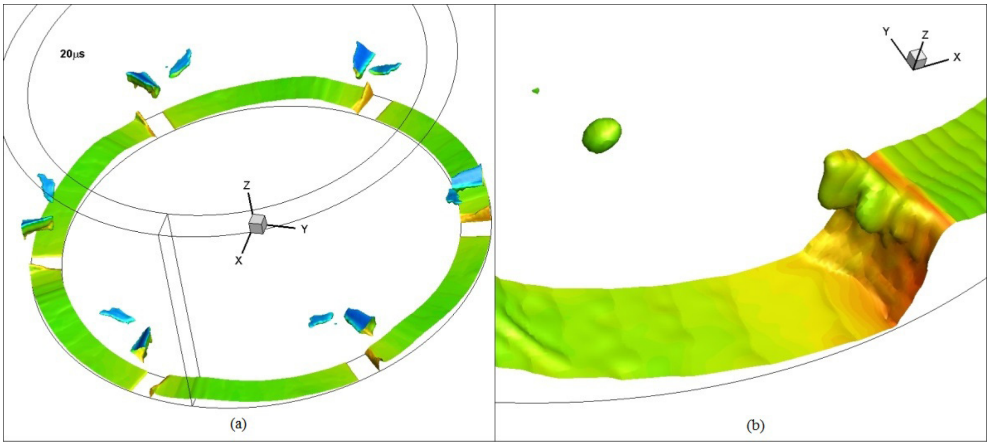

Fig. 3 The contours of the extent of the chemical reaction under 20atm inlet pressure.

4. Conclusions

In consideration of the influence of the inlet total pressure and the number of detonation waves on RDE's operation, we proposed a series of numerical cases. Our study concluded as follows:

1. The number of detonation waves had little effect on the specific impulse, the thrust and the outlet flow under the same inlet total pressure, but influenced the required time to reach stable detonation.
2. The inlet total pressure restricted the fuel gas intake, thus affecting the energy of detonation waves. The lower inlet total pressure usually led to unstable combustion phenomenon.
3. For fuel injection, the inlet total pressure should match with the ignition to accelerate the stability of detonation waves.

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