Numerical and theoretical studies of a hydrogen-air rotating detonation engine

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1 Abstract

The flow field of a premixed hydrogen-air rotating detonation engine (RDE) was studied through simulations and theory. The theoretical and numerical results, including deflection angles and pressure behind waves, match each other well. The theoretical method instead of expensive simulations can obtain a rough flow field of the rotating detonation engine, including the detonation wave, oblique shock wave, and deflected contact surface.

2 Introduction

Detonative combustion has several advantages over deflagrative combustion. Detonation may increase the total pressure in the combustion chamber and produce a higher propulsion performance. RDEs fueled by hydrogen are widely studied since it is easy to produce rotating detonation waves. In the 1950s, Voitsekhovskii of the Soviet discovered the phenomenon of rotating detonation in a liquid rocket engine. Subsequently, the research group successfully obtained the continuous rotating detonation waves through the disk-type experiment device operating on C_2H_2/O_2 mixtures [1]. In the studies of RDE fueled with H_2, many investigators utilized the slit for oxidizer injection and orifices for H_2 [2, 3]. The band distribution of H_2 [4] or O_2 [5] in the combustion chamber occurred. There are rotating detonation waves, oblique shock waves and contact surfaces in the combustor. In this paper, numerical and theoretical studies on the RDE flow field were carried out to verify the theory.

3 Physical model and validation

Because of the low cost, the thrust performance [6], thermodynamic performance [7] and flow field of RDEs were studied using 2D models in many numerical simulations. Figure 1 shows the two dimensional model of the RDE. The length is L=200 mm, the height is H=50 mm, the inlet mass flow rate is 50 kg/s, the inflow temperature is 300 K, the total pressure is 0.1 MPa and the equivalent ratio is 1.0. The inviscid model and a simplified reaction mechanism for ideal hydrogen-air mixture are used. The numerical detonation cell size of 8.32 mm in Fig. 2 is close to the experimental value of 8.2

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mm [8]. In order to further analyze the characteristics of the flow field, and evaluate numerical results, the deflection angle of the detonation flow field is studied theoretically.

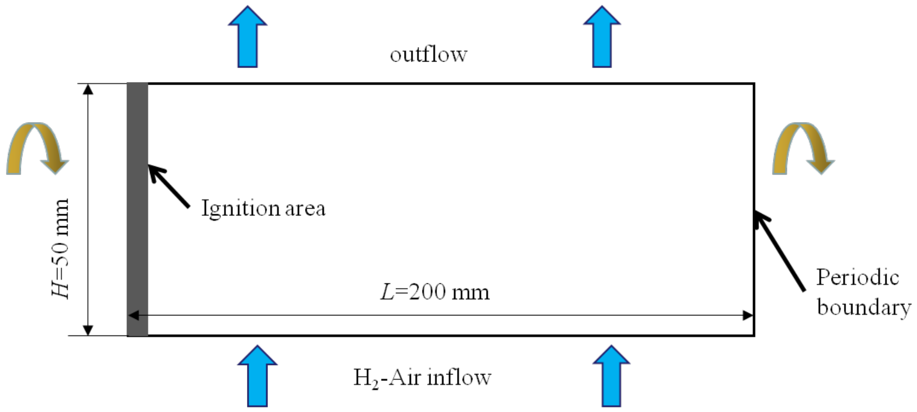


Figure 1: Two dimensional model of the RDE.

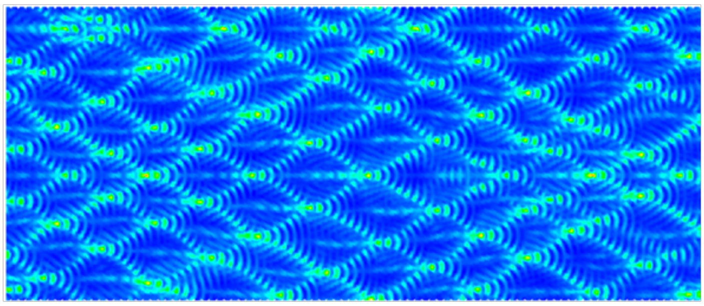


Figure 2: Detonation cells for hydrogen-air mixture.

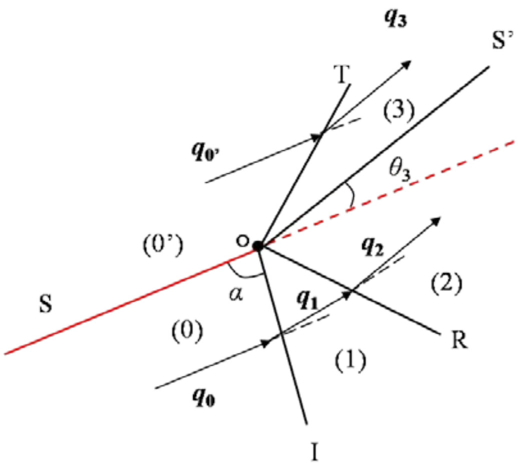
4 Analytical study

The parameters of the detonation wave derived from GASEQ and numerical flow-field are described in Table 1. Parameters in zone 1 near OR are used here considering the inhomogeneity of zone 1.

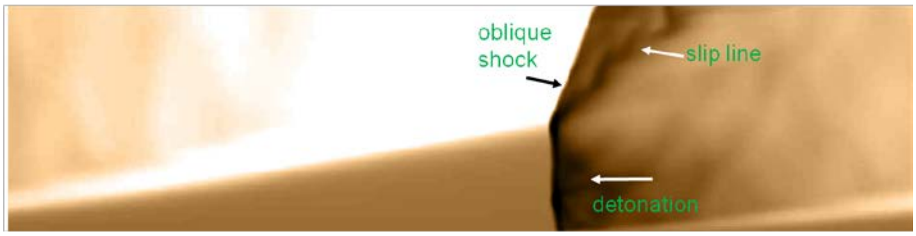
Table 1: Parameters of the hydrogen-air detonation wave

Type	Zone 0	Zone 1	Zone 1(near OR)
Pressure(atm)	1	15.085	11
Mach number	4.843	1	1.13
Velocity(m/s)	1979.33(shock wave)	1130.59(gas)	1046.29(gas)
Density(kg/m^3)	0.8496	1.48736	1.25
γ(specific heat ratio)	1.401	1.244	1.244

The ideal gas is used. As shown in Fig. 3, a moving coordinate system attached with the intersect point O of the shock wave OI and the contact surface OS is chosen. OS is the undisturbed interface. OT is a refracted shock wave. OR is a reflected wave (shock wave or expansion wave). OS' is the contact surface disturbed. The waves and interfaces divide the flow field near the O point into five regions. Zone 0 is the area of the fresh reactants in front of the detonation wave. Zone 0' is the product expansion area in front of the refracted shock wave. Zone 1 is behind the detonation wave. Zone 2 is behind the reflected wave. Zone 3 is the region between OT and OR.
In addition, $\boldsymbol{q_i}$ is the fluid velocity, i=0, 1, 2, 3, θ_1 is the deflection angle of $\boldsymbol{q_1}$ relative to $\boldsymbol{q_0}$. θ_2 is the deflection angle of $\boldsymbol{q_2}$ relative to $\boldsymbol{q_1}$. θ_3 is the deflection angle of $\boldsymbol{q_3}$ relative to $\boldsymbol{q_0}$. α is the angle between OI and $\boldsymbol{q_0}$.



(a)



(b)

Figure 3: RDE flow field. (a) Theoretical flow, (b) simulation flow.

A relevant theoretical model for the subsequent analysis in this paper was used [9]. α was given by:

$$\sin\alpha = \frac{1}{q_0}\frac{p_1 - p_0}{\rho_0\left(1-\frac{\rho_0}{\rho_1}\right)} \tag{1}$$

where ρ *is* density, p is pressure. The post-detonation conditions are given by Eq. 2:

$$\tan\theta_1 = \pm\frac{\sqrt{2\frac{p_1}{p_J}-1-\left(\frac{p_1}{p_J}\frac{D}{q_0}\right)^2}}{\frac{(\gamma+1)q_0}{D}-\frac{p_1}{p_J}\frac{D}{q_0}} \tag{2}$$

where D is detonation speed, the subscript J corresponds to the Chapman-Jouguet detonation. The post-shock conditions and the post-expansion conditions are given by Eqs. 3 and 4, respectively. The Eq. 3 is derived from Hugoniot equation and Eq. 4 is derived using the Bernoulli equation, the isentropic equation, and the Riemann invariant.

$$\tan\theta_2 = \pm\frac{\frac{p_2}{p_J}-1}{\gamma M_1^2-\left(\frac{p_2}{p_J}-1\right)}\sqrt{\frac{\frac{2\gamma}{\gamma+1}\left(M_1^2-1\right)-\left(\frac{p_2}{p_J}-1\right)}{\frac{p_2}{p_J}+\frac{\gamma-1}{\gamma+1}}} \tag{3}$$

$$\theta_2 = \theta_1 + \arctan\frac{c_2}{\sqrt{\frac{\gamma+1}{\gamma-1}\left(c_*^2-c_2^2\right)}} - \arcsin\frac{1}{M_1} + \sqrt{\frac{\gamma+1}{\gamma-1}}\left(\arccos\frac{c_2}{c_*}-\arccos\frac{c_1}{c_*}\right) \tag{4}$$

where $M_1=q_1/c$, c is acoustic speed, $p_J=\frac{\rho_0 D^2}{\gamma+1}$, $p_2=p_J\left(\frac{c_2}{c_J}\right)^{\frac{2\gamma}{\gamma-1}}$ and the ultimate sound speed c_* was given as:

$$c_*^2 = \frac{\gamma+1}{\gamma-1}c_J^2\left[M_1^2+\frac{2}{\gamma-1}\right] \tag{5}$$

5 Results and discussions

The deflection angle is a function of pressure behind OR and OT in Fig. 4. In Fig. 4, curves of the reflect shock wave and expansion wave are denoted by OR(S) and OR(R), respectively. I(θ_1, p_1) point serves as the starting point of the reflected wave. The intersection C corresponds to the conditions in zone 2 and 3. α=80°, θ_1= 6.84°.

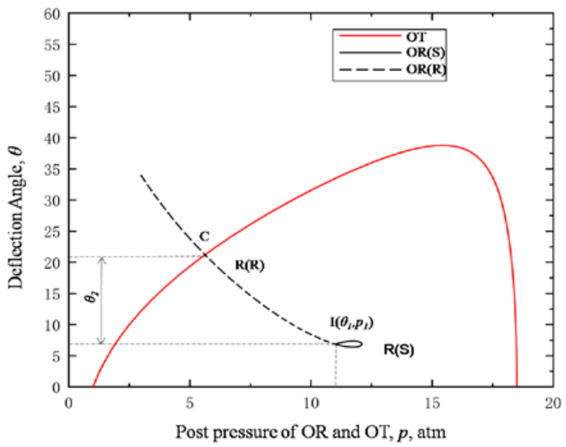


Figure 4: Deflection angle plotted as a function of pressure behind OR and OT

The theoretical and numerical results are shown in Table 2.

Table 2: Theoretical and numerical results

Variable	Theoretical value	Numerical value
θ_2, °	14.16	11~14
θ_3, °	21	20~28.5
p_2, atm	5.7	5~6.3
p_3, atm	5.7	5~6.3

Sommers and Morrison noted that this system resembles the interaction of a shock wave incident on a free boundary and may be solved in a similar manner, which account for the appearance of oblique shock and slip line [10]. The inclusion of reactants injected in front of the detonation adds a vertical component of the velocity ahead of the detonation wave. This inclines the detonation and generates a second expansion fan that emanates from the bottom of the detonation and turns the flow parallel to the wall [11]. The theoretical and simulation results show that the reflected wave OR is a rarefaction wave. The deflection angles change slightly with the rate of reaction.

4 Conclusion

Comparisons between theoretical and numerical results show that theoretical method can be used to analyze the RDE flow field, including the angle of the contact surface and the oblique shock, the pressure behind the oblique shock, the reflected rarefaction wave from the contact surface. The theoretical method provides a cheaper and faster tool to obtain the flow of the RDE. However, this applies to premixed detonation and ignores deflagration. Comprehensive data are being calculated in order to obtain more information of flow field. More details will be presented at the ICDERS 2023.

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