Numerical Analysis of the Influence of Mixing on Detonation Wave Propagation inside a Rotating Detonation Engine by using Linear Detonation Channel

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1 Introduction

In recent years, detonation engines have been favored by researchers because of their simple structure and high efficiency. Among them, the Rotating detonation engine (RDE) has the potential to completely replace the existing technology of traditional aerospace engines. In the future, it may become the main engine application in aviation, aerospace and other fields. At present, Russia, Poland, China, the United States and other countries have carried out a large number of RDE-related research work and have made great progress. In Japan, Japan Aerospace Exploration Agency (JAXA) also has great interest in Rotating Detonation Engine (RDE) and has begun basic research. Currently, RDE has been successfully run at JAXA Kakuda Space Center [1].

Although there are many research results on RDE in various countries, propagation of the explosion wave inside the RDE has not been clearly revealed through experiments, because the propagation of the rotating detonation wave is affected by the injection pressure, the curvature of the combustion channel and the fuel-oxidant mixture ratio. The explosion wave speed generated in the RDE is usually Significantly lower than the characteristic Chapman-Jouguet (C-J) velocity of the corresponding mixture, RDE has not been practical yet.

The objective of this study is to examine the reduction in the propagation velocity of detonation waves caused by partially mixed reactant species. The method is to simplify the complex annular RDE flow field into a linear flow field and observe the influence of the incomplete mixing of fuel and oxidant in the RDE on the propagation of detonation waves by means of optical visualization. In this paper, performed a high-precision analysis of the detonation propagation in linear detonation channel by using JAXA 's in-house code CHARIOT [2-3].

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2 Linear Detonation Channel

The linear detonation channel facility is shown in Figure1. It's unfolds a curved RDE combustion chamber into a linear shape.The fuel and oxidant enter the tube through a small hole at the bottom with a controllable flow rate, and it's possible to change its ignition mode by changing some parts Both sides are equipped with quartz windows for optical visualization.

The advantage of the linear detonation channel is that the propagation of the detonation wave inside the channel is not affected by the shape and centrifugal force, and the observation windows on both sides of the passage can perform more clearer optical visualization.

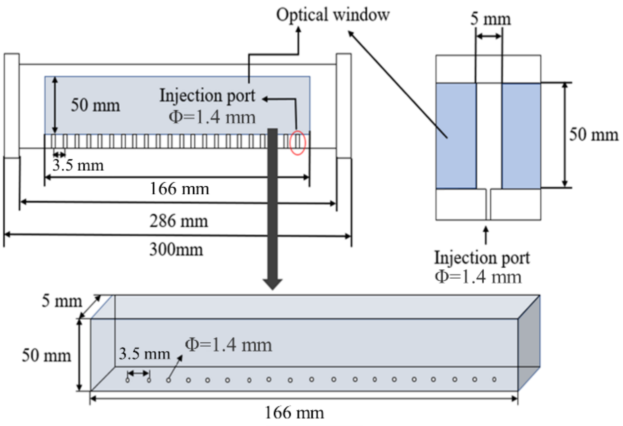


Figure 1: Linear detonation channel.

3 Numerical Analysis Method

In numerical analysis, we used JAXA's in-house code CHARIOT (Cost-effective High-order Accurate Reconstruction-scheme Intensively Optimized for Turbulent-combustion) that designed for DNS/LES of turbulent combustion in aerospace propulsion systems. The governing equations of the flow used for the present LES analysis is compressible Navier-Stokes equation:

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial\bar{\rho}\tilde{u}}{\partial x_i}=0$$

$$\frac{\partial\bar{\rho}\tilde{u}_i}{\partial t}+\frac{\partial}{\partial x_j}\{\bar{\rho}\tilde{u}_i\tilde{u}_j+\bar{p}\delta_{ij}-\bar{\tau}_{ij}+\bar{\rho}(\widetilde{u_i u_j}-\tilde{u}_i\tilde{u}_j)\}=0$$

$$\frac{\partial\bar{\rho}\tilde{e}}{\partial t}+\frac{\partial}{\partial x_i}\{\bar{\rho}\tilde{u}_i\tilde{e}+\bar{p}\tilde{u}_i+\bar{q}_i-\tilde{u}_j\bar{\tau}_{ij}+\bar{\rho}(\widetilde{e u_i}-e\tilde{u}_i)\}=0$$

$$\frac{\partial\bar{\rho}\tilde{Y}_k}{\partial t}+\frac{\partial}{\partial x_i}\left\{\bar{\rho}\tilde{Y}_k\tilde{u}_i-\bar{\rho}\tilde{D}_k\frac{\partial\tilde{Y}_k}{\partial x_i}+\bar{\rho}(\widetilde{Y_k u_i}-\tilde{Y}_k\tilde{u}_i)\right\}=\overline{\dot{\omega}_k}$$

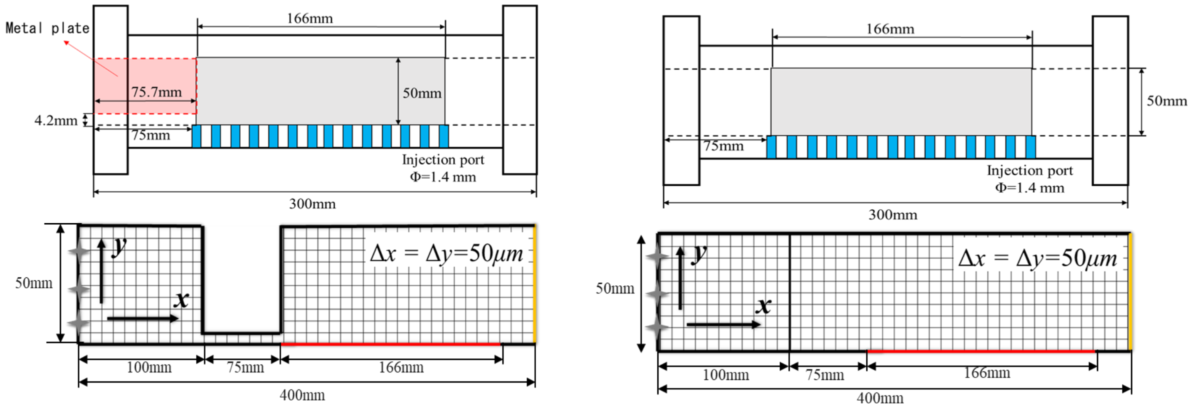
LES analysis in this study is performed by implicit LES, in which all SGS terms are set to zero. For the detailed reaction model of ethylene combustion, 126 species reactions model is used. In addition, operator-splitting method, and a Quasi-Steady-State approximation (QSS) [4] are applied to reduce the stiffness associated with fast chemical reactions. The CHEMKIN database [5-6] is used to calculate the thermodynamic and transport properties.

The governing equations are discretized by the finite volume method. The convective flux is calculated by SLAU2 scheme [7], and the viscous flux is obtained by the central difference method. High order spatial accuracy is realized by interpolating primitive variables (ρ, u, v, w, p, Ys) at the cell interface [8]. For the scalar variables (ρ, p, Ys), the second-order MUSCL (Monotone Upwind Scheme for Conservation Laws) method is used, and the velocity components (u, v, w) are interpolated with a fifth order polynomial. In addition, to reduce the numerical dissipation in low velocity flow, the correction method by Thornber et al [9]. is applied to interpolated velocity components. For the time integration method, the three-stage Runge-Kutta method is employed.

Computation was carried out on the JAXA Supercomputer System (JSS3) installed at the Aeronautical Technology Directorate (ATD) of JAXA. Parallel computation was implemented by domain decomposition, with the Message Passing Interface (MPI) library used for inter-processor communication.

4 Numerical analysis model & injection conditions

The above device has two ignition modes by changing the components. Mode 1 is to insert a metal plate to make a long and narrow flow path to simulate actual RDE ignition, and Mode 2 is to directly ignite by connecting other detonation tubes. The two modes of the device and the corresponding calculation model are shown in Figure 2. In the calculation model, the mark on the left is the ignition position, the black line is the solid wall, the red line is inflow boundary same as the fuel injection method of the device, and the yellow line is the outflow boundary. In the past calculations on the detonation structure, the grid accuracy of 50 µm was sufficient, so the grid accuracy of this calculation is also set to 50 µm. The injection conditions for numerical analysis are shown in Table 1. The fuel injector is set to 90°, 70°, and 45° injection.



(a) Mode 1 (b) Mode 2

Figure 2: Device mode with Numerical analysis model.

Table 1: Injection condition.

Number of grid	8009001		
grid width	50 µm		
Fuel-oxidizer	Ethylene-Oxygen		
Equivalent ratio	1.0		
Filling pressure	0.1 MPa		
Mass flow rate	15 g/s	20 g/s	60 g/s

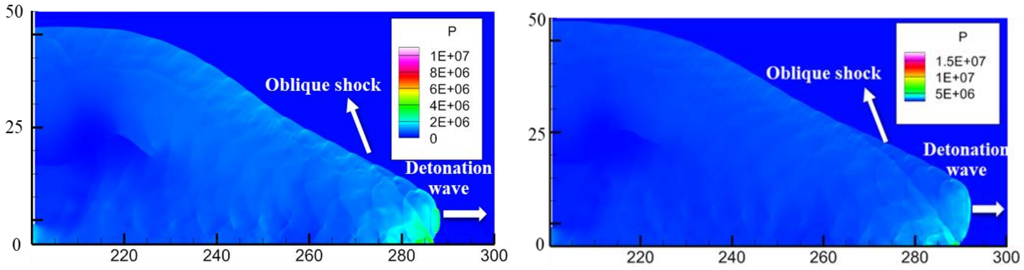
5 Numerical analysis results

5.1 Premixed gas injection

To analyze the effect of incomplete mixing of fuel and oxidant on the propagation of detonation waves, we first carried out a numerical analysis of the propagation of detonation waves in premixed fuel. Considering that premixed fuel does not need to promote mixing, this term only performs calculations for gas injection perpendicular to the bottom.

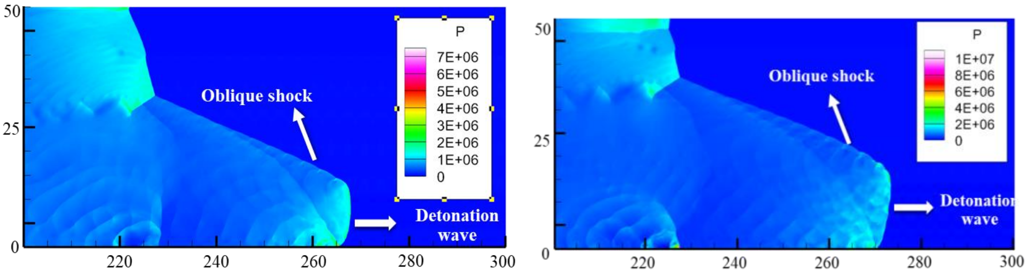
The results shown in Figure 3 and Figure 4 are obtained through two different modes by numerical analysis, can see that after the detonation wave enters the area of fuel injection, the fuel is ignited, and the detonation wave is maintained and propagated.

The detonation propagation velocity has obvious differences in the same mode with different mass flow rates and the same mass flow rate with different modes. The numerical analysis results of the detonation velocity are shown in Table 2.



(a) $\dot{m}$ = 15 g/s (b) $\dot{m}$ = 20 g/s

Figure 3: Numerical results of premixed (mode 1).



(a) $\dot{m}$ = 15 g/s (b) $\dot{m}$ = 20 g/s

Figure 4: Numerical results of non-premixed (mode 2).

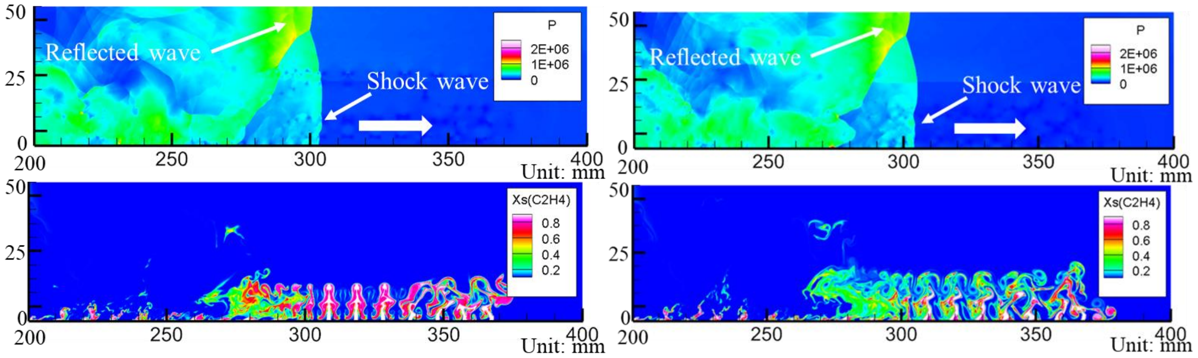
Table 2: Numerical analysis results of detonation velocity (Premixed gas injection).

Mode	Mode 1		Mode 2	
Mass flow rate	15 g/s	20 g/s	15 g/s	20 g/s
Detonation velocity	1976 m/s	1833 m/s	1983 m/s	2243 m/s

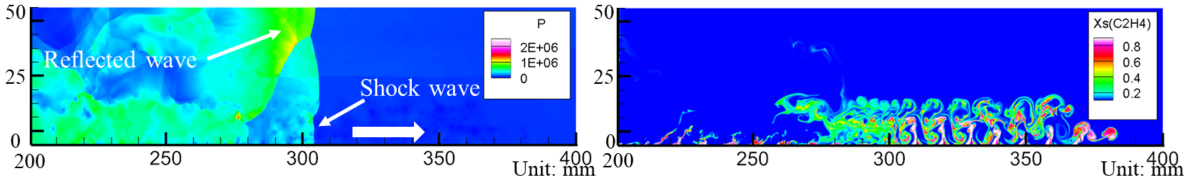
5.2 Non-premixed gas injection

The numerical analysis results of non-premixed gas injection are shown in Table 3 and Figure 5, 6. The injected fuel was successfully ignited, however the propagation velocity of the wavefront was significantly slowed down at low mass flow rates, shock wave and combustion wave were separated and detonation wave propagation could not be maintained. The cause is that the flow velocity of the fuel is limited to within the supersonic, so it is much smaller than the actual mass flow rate of RDE. Concurrently, the results also clearly show that the combustion is greatly improved after changing the roll angle of the fuel injection to improve the mixing state of the fuel. In addition, the mixing state of fuel and oxygen in the field between shock wave and combustion wave is significantly improved compared with the mixing state before the shock wave. The promoting effect of the shock wave on the fuel mixing can be confirmed.

After increasing the fuel mass flow rate to the same level as RDE as shown in Figure 6, Detonation propagation be maintained. However, the detonation wave velocity is not as high as that of the premixed injection, only reaching 80% of the theoretical C-J velocity.



(a) Pressure and fuel distribution of 90°. (b) Pressure and fuel distribution of 70°.



(c) Pressure and fuel distribution of 45°.

Figure 5: Numerical results of non-premixed ($\dot{m}$ = 20 g/s).

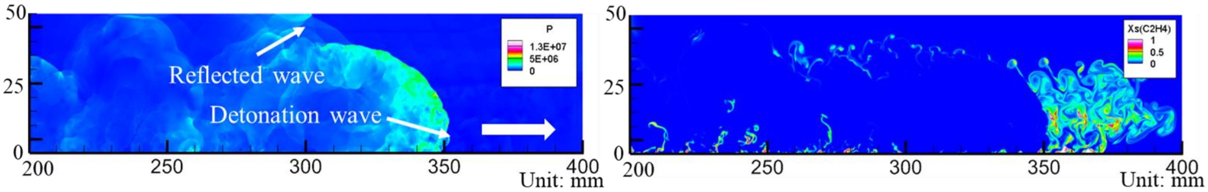


Figure 6: Numerical results of non-premixed ($\dot{m}$ = 60 g/s).

Table 3: Numerical analysis results of detonation velocity (Non-premixed gas injection).

Injector angle	90°	70°	45°	
Mass flow rate	20 g/s	20 g/s	20 g/s	60 g/s
Detonation velocity	1478 m/s	1482 m/s	1497 m/s	2041 m/s

6 Conclusions

Numerical analysis of detonation wave propagation in linear detonation channel was carried out. Brief conclusions could be drawn as follows:

The ignition of the fuel in the combustion chamber and the formation of detonation propagation has a very high dependence on the ignition source energy, When the ignition energy is insufficient, the detonation will not occur or need a longer path to reach the expected value. In the case of premixed injection, detonation velocity able to reach more than 90% of the theoretical value. Compared with the traditional RDE using non-premixed fuel injection, the improvement is obvious. This shows that when the fuel is completely mixed, the propagation speed of detonation will be greatly improved. If the existing RDE fuel injection method can be improved to make the fuel mixing more fully, the performance of the RDE will also be improved.

In the case of non-premixed injection using doublet injectors, the mixing condition was significantly improved as the angle of opposite direction increased, and it was confirmed that the shock wave promoted the fuel mixing. However, non-premixed fuels require high mass flow rates of fuel and oxidant to maintain detonation wave propagation, which will inevitably generate shock waves and affect the results. We will evaluate this part of the impact in the future work.

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