33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

Numerical Analysis of Propagation of Detonation Wave Plunging Entry the Fuel Jet Train inside Rotating Detonation Combustor

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Abstract

In the flow field of a rotating detonation engine (RDE), the detonation wave propagates through the reaction with the continuously injected fuel and oxidant mixture. In the previous research using the actual RDE, since the fuel used in RDE is usually non-premixed, insufficient mixing of the fuel with the oxidant results the detonation wave velocity generated in RDE is usually significantly lower than the characteristic Chapman-Jouguet (C-J) velocity for corresponding mixture. In this paper, to clarify the effect of detonation propagation by incomplete fuel mixing in RDE, construct a linear detonation channel that simulate the RDE flow field and carried out a numerical analysis of propagation of detonation wave plunging entry the premixed and non-premixed combustible gas jet train. By promoting the mixing of the fuel, the propagation velocity of the detonation wave in the non-premixed fuel condition reaches 93% of the C-J velocity.

Keywords: Pressure gain combustion, Detonation engine, Doublet injectors

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].

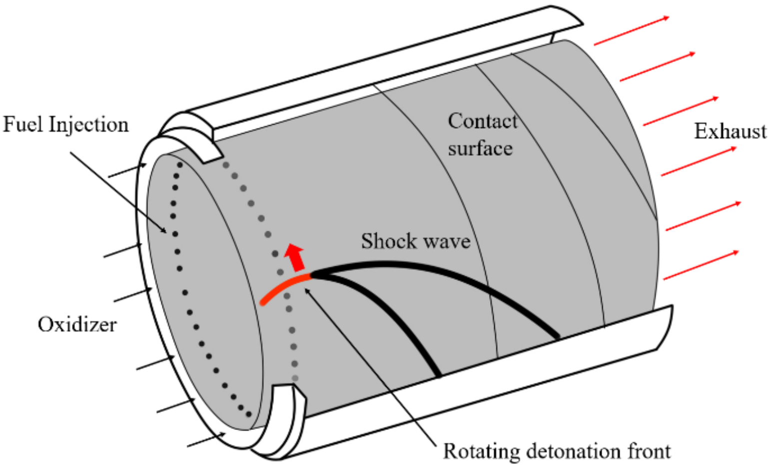


Figure 1 – Rotating Detonation Engine.

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 wave 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 fuel. The method is to expand the annular rotating combustor (RDC) of the RDE into a linear detonation channel to eliminate the influence of shape and centrifugal force on the propagation of detonation, so that could investigate the influence of fuel on the propagation of detonation waves in detail. To clarify the influence of incomplete fuel mixing on the propagation of detonation. In this paper, performed numerical analysis of propagation of detonation wave plunging entry the combustible jet train with different injection angles and mixing states by using a supercomputer system.

2. Linear detonation channel

The linear detonation channel (LDC) facility is shown in Figure 2. It's unfolding 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 LDC 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.

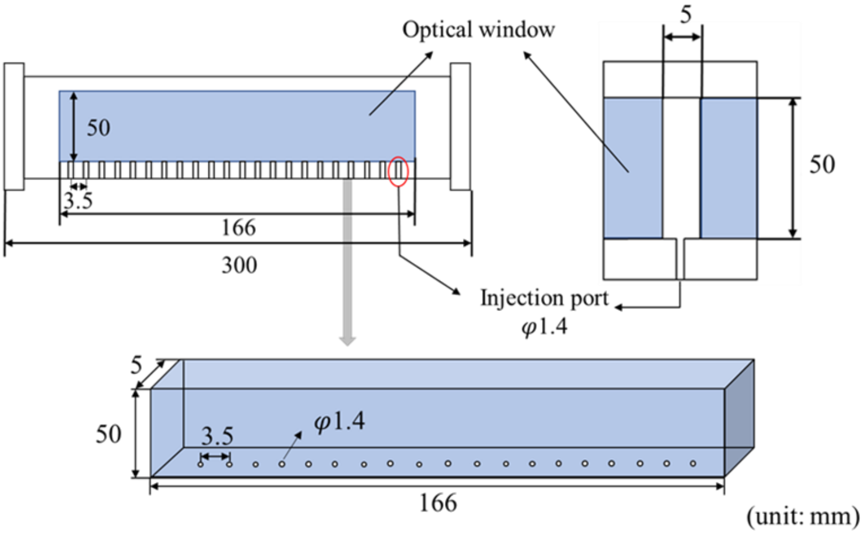


Figure 2 – Linear detonation channel.

3. Numerical Analysis Method

Numerical analysis is performed by using 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 three-dimensional filtered compressible Navier-Stokes equation.

$$\frac{\partial \bar{\rho}}{\partial t}+\frac{\partial \bar{\rho}\tilde{u}_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t}+\frac{\partial}{\partial x_j}\left\{\bar{\rho}\tilde{u}_i\tilde{u}_j+\bar{p}\delta_{ij}-\bar{\tau}_{ij}+\bar{\rho}\left(\widetilde{u_i u_j}-\tilde{u}_i\tilde{u}_j\right)\right\}=0 \tag{2}$$

$$\frac{\partial \bar{\rho}\tilde{e}}{\partial t}+\frac{\partial}{\partial x_i}\left\{\bar{\rho}\tilde{u}_i\tilde{e}+\bar{p}\tilde{u}_i+\bar{q}_i-\tilde{u}_j\bar{\tau}_{ij}+\bar{\rho}\left(\widetilde{e u_i}-e\tilde{u}_i\right)\right\}=0 \tag{3}$$

$$\frac{\partial \bar{\rho}\tilde{Y}_k}{\partial t}+\frac{\partial}{\partial x_i}\left\{\bar{\rho}\tilde{Y}_k\tilde{u}_i-\bar{\rho}\tilde{D}_k\frac{\partial \tilde{Y}_k}{\partial x_i}+\bar{\rho}\left(\widetilde{Y_k u_i}-\tilde{Y}_k\tilde{u}_i\right)\right\}=\overline{\dot{\omega}_k} \tag{4}$$

Although the unclosed SGS terms, $\bar{\rho}\left(\widetilde{u_i u_j}-\tilde{u}_i\tilde{u}_j\right)$, $\left(\widetilde{e u_i}-e\tilde{u}_i\right)$, and $\bar{\rho}\left(\widetilde{Y_k u_i}-\tilde{Y}_k\tilde{u}_i\right)$, are usually included in the filtered governing equations, 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, 31 species and

126 species reactions model is used. In addition, operator-splitting method and a Quasi-Steady-State approximation (QSS) are applied to reduce the stiffness associated with fast chemical reactions. The CHEMKIN database 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, 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. 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. 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

By inserting a metal plate upstream of the detonation flow of the above device, a long and narrow flow path is formed to simulate the actual RDE ignition. The schematic diagram of the device and its corresponding calculation model are shown in Figure 3. In the calculation model, the star-shaped mark on the left is the ignition position, the black line is the solid wall, the red line is the inflow boundary, and the yellow line is the outflow boundary. In the previous research of Two-dimensional numerical analysis of detonation structure, the error between the detonation pressure history of the numerical analysis results and the experimental value is within 10% under the grid accuracy of 50 μm[2]. so the grid accuracy of this calculation is also set to 50 μm. The injection conditions of the numerical analysis are shown in Table1. The fuel injection can be set to 90-degree to 45-degree injection shown in Figure 4.

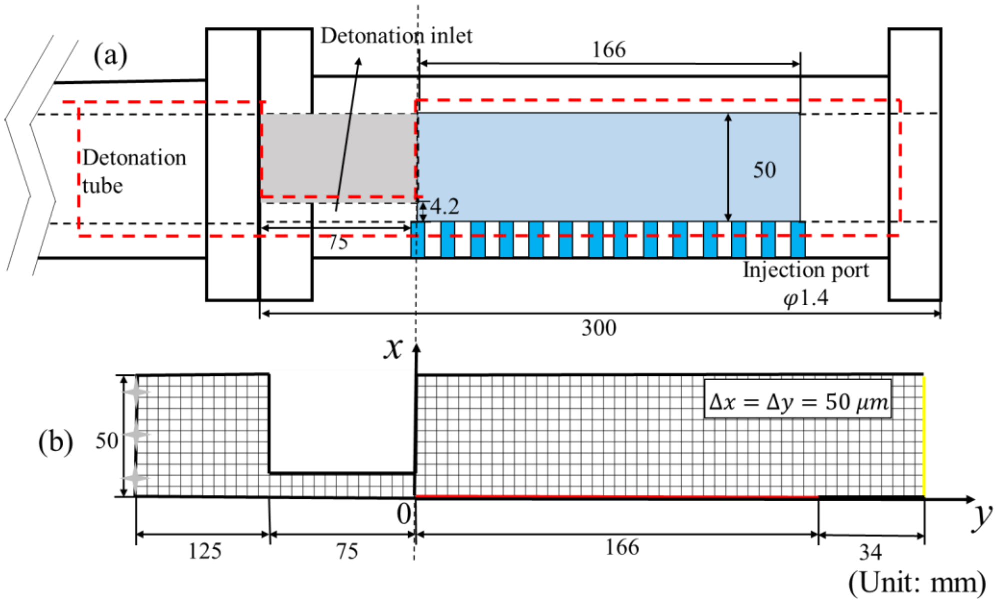


Figure 3 – computational model. (a) Outline of the experimental setup; (b) Computational grid.

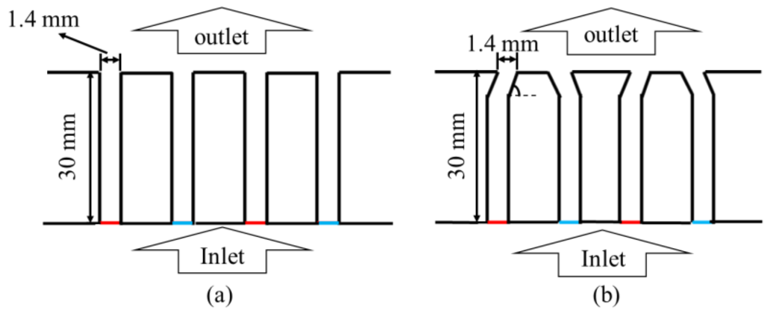


Figure 4 – Injection model.

Table 1 Injection conditions for CFD.

Injection conditions	
Number of gird	8001 x 1001
Grid width	50 μm
Fuel-Oxid.	Ethylene-Oxygen
Equivalent ratio	1
Filling pressure (Detonation tube)	0.1 MPa
P_0 (LDC)	1 atm.

5. Numerical Analysis Results

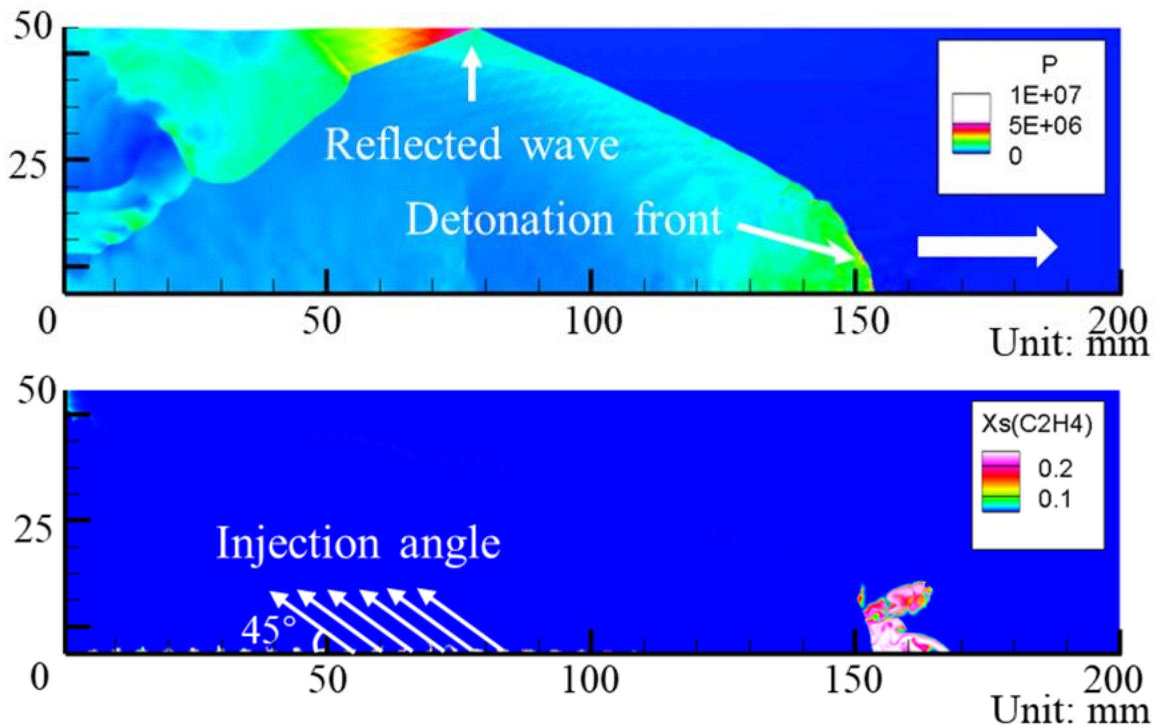
5.1 Premixed fuel injection

The numerical analysis results of Premixed fuel injection are shown in Table 2 and Figure 5. The injected fuel is successfully ignited, and the detonation wave is maintained and propagated. In this calculation, the angles of adjacent jets are not opposite, and all jets have the same angular direction. A difference was shown in the propagation velocity of the detonation wave depending on the injection angle of the fuel. The effect of the detonation wave pressure on the fuel injection is the largest when the injection port is at an angle opposite to the detonation wave propagation direction, and the detonation propagation velocity is the lowest.

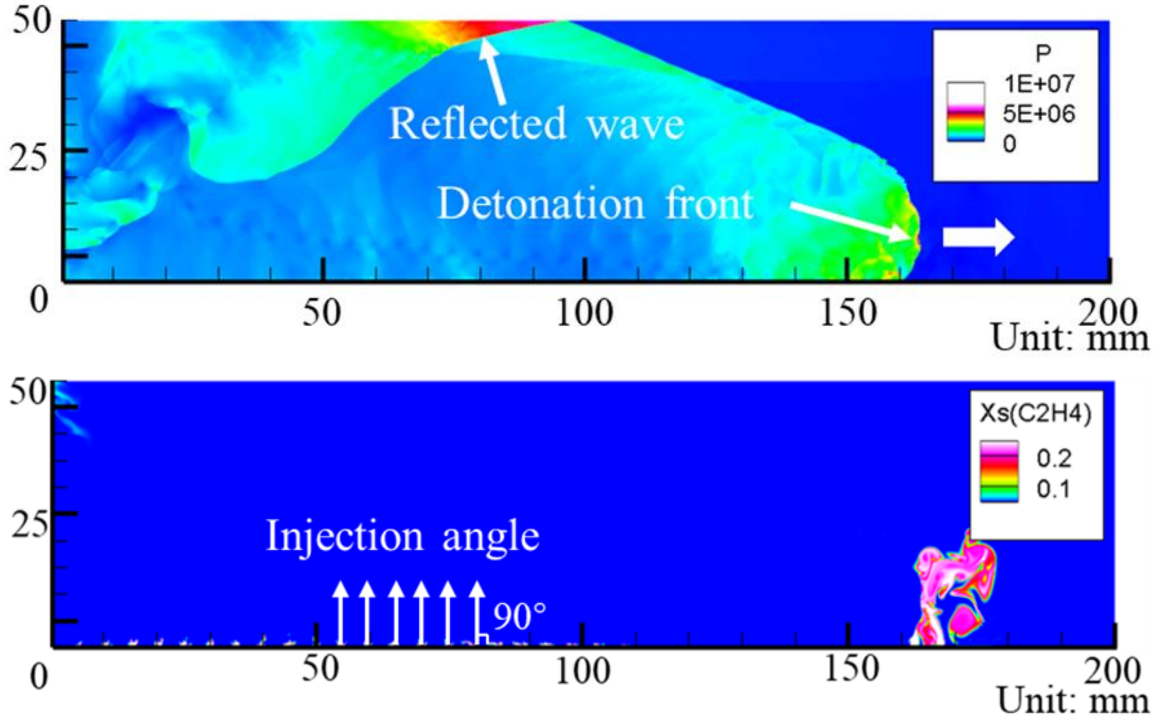
In the premixed fuel injection train, the fuel distribution of the burnt gas behind the detonation wave in each case indicates that the combustion is complete combustion. The detonation velocity in each case reached 93% -98% of the C-J theoretical value.

Table 2 Results of detonation velocity (Premixed gas injection).

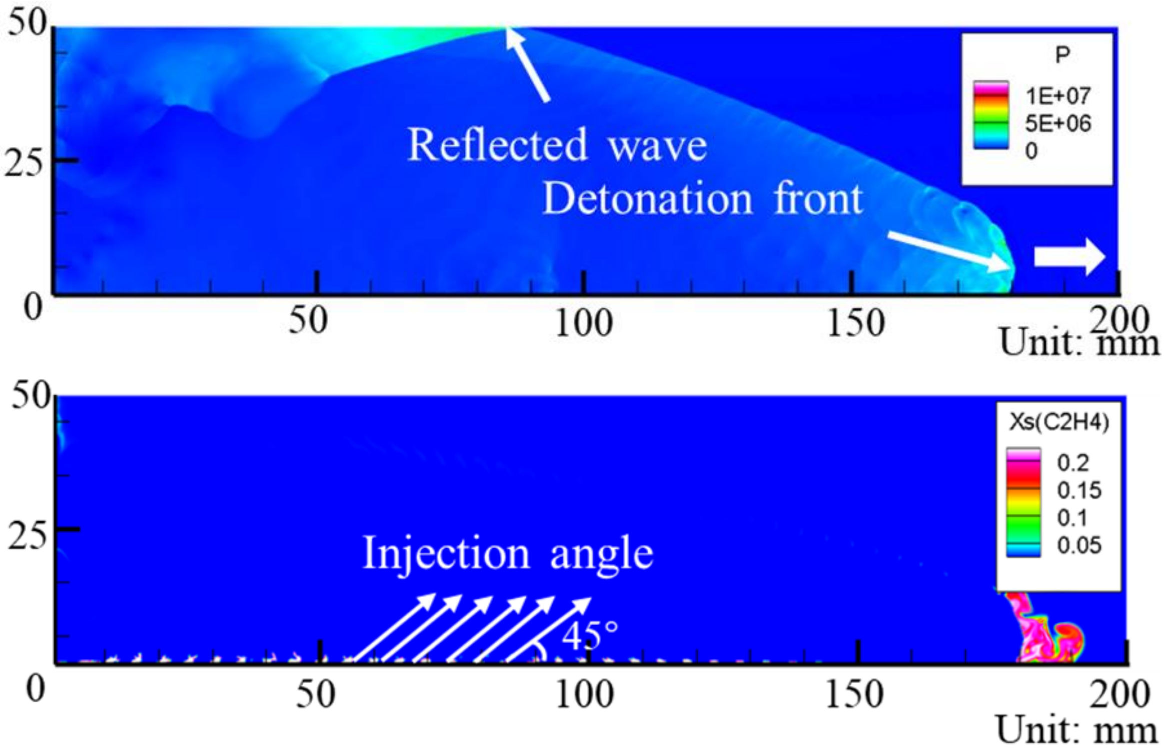
Injection port angle	45°L	90°	45°R
Detonation velocity	2291 m/s	2353 m/s	2397 m/s
C-J velocity	2439 m/s		



(a) Pressure distribution and fuel distribution at injection angle of 45°L.



(b) Pressure distribution and fuel distribution at injection angle of 90°.



(c) Pressure distribution and fuel distribution at injection angle of 45°R.

Figure 5 – Numerical results of premixed gas injection.

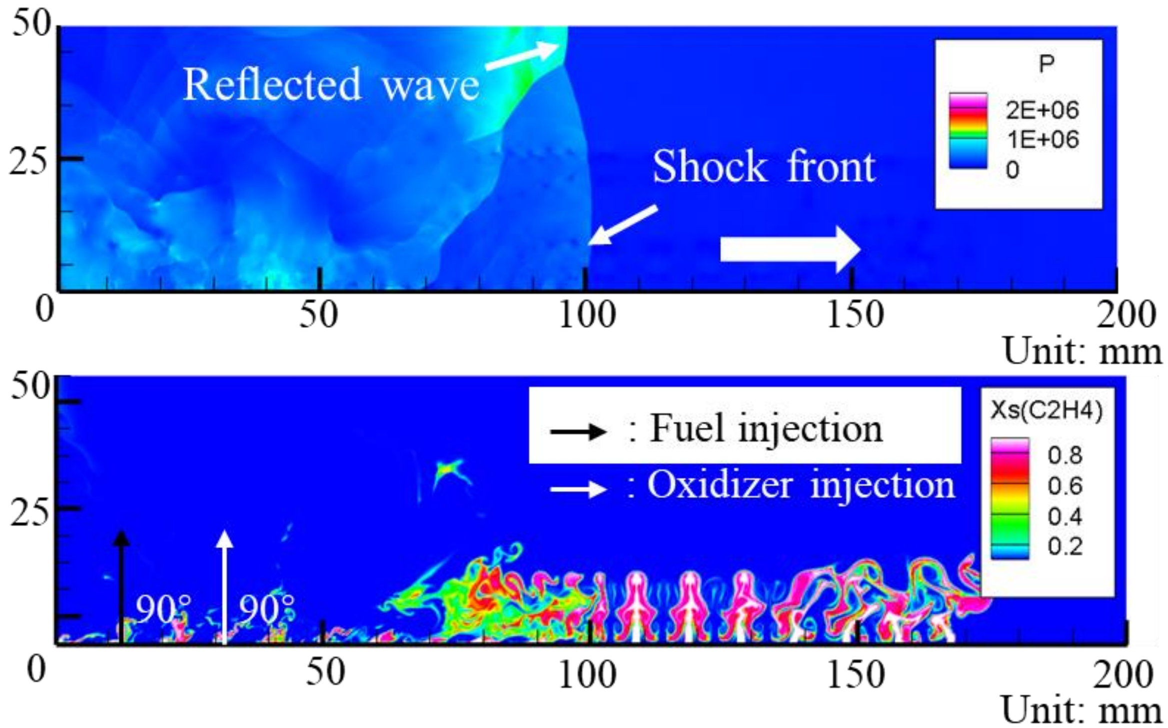
5.2 Non-premixed gas injection

The numerical analysis results of non-premixed gas injection are shown in Table 3 and Figure 6. The injected fuel was successfully ignited, however 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.

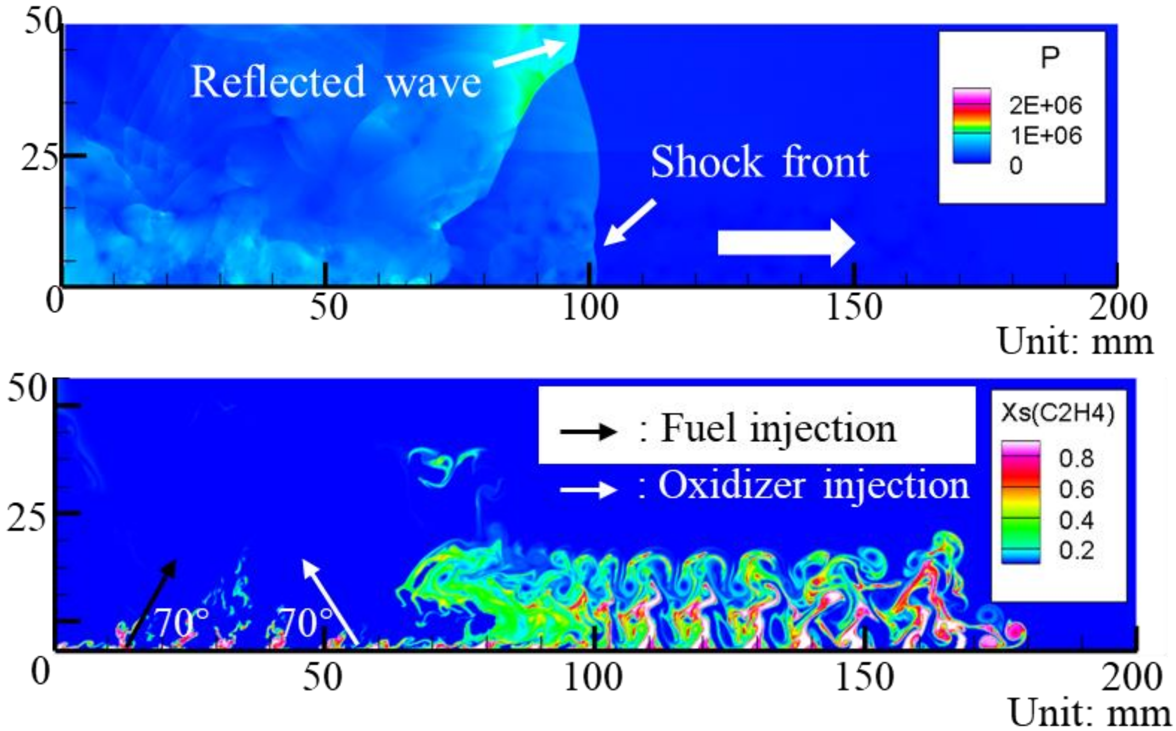
Concurrently, the results show that fuel mixing is improved by opposed injection of fuel and oxidizer. In addition, the mixing state of fuel and oxygen in the field between shock wave and combustion wave is significantly improved compared with the mixing state before the shock wave front. The promoting effect of the shock wave on the fuel mixing could be confirmed.

Table 3 Results of detonation velocity (non-premixed gas injection).

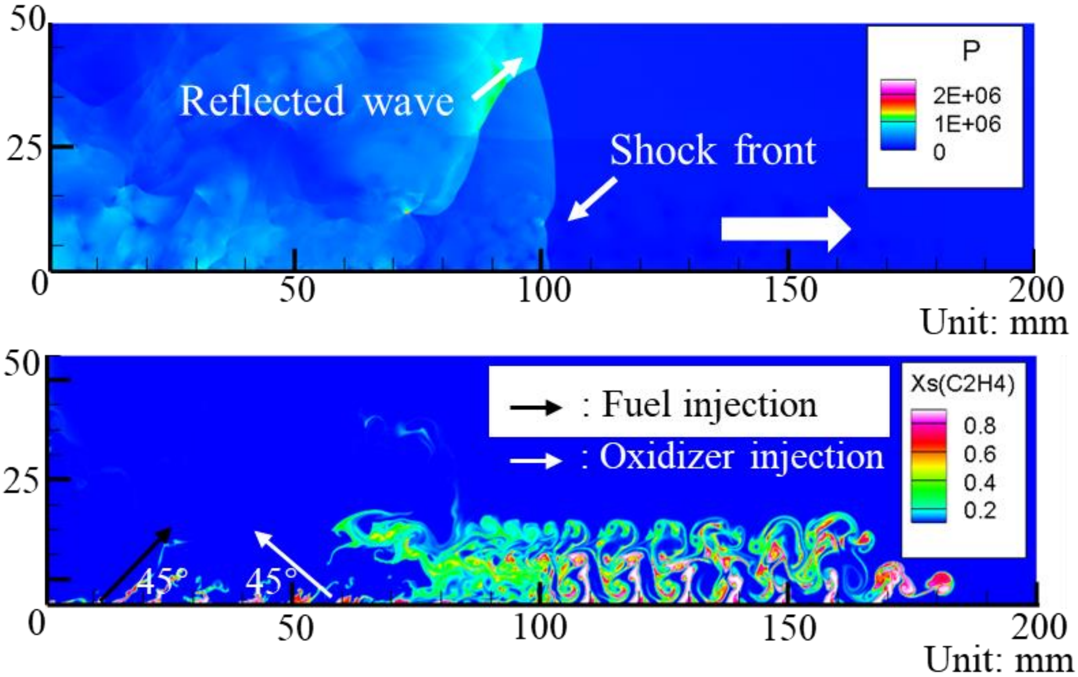
Injection port angle	90°	70°	45°
Front velocity	1511 m/s	1547 m/s	1552 m/s



(a) Pressure distribution and fuel distribution at injection angle of 90°.



(b) Pressure distribution and fuel distribution at injection angle of 70°.



(c) Pressure distribution and fuel distribution at injection angle of 45°.

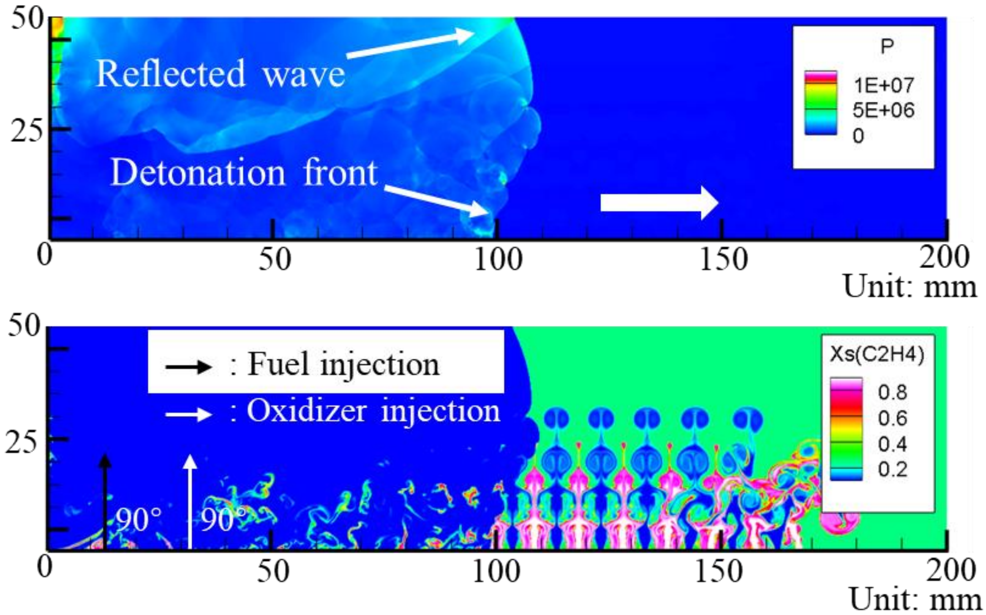
Figure 6 – Numerical results of non-premixed gas injection.

5.3 Non-premixed gas injection with premixture filling

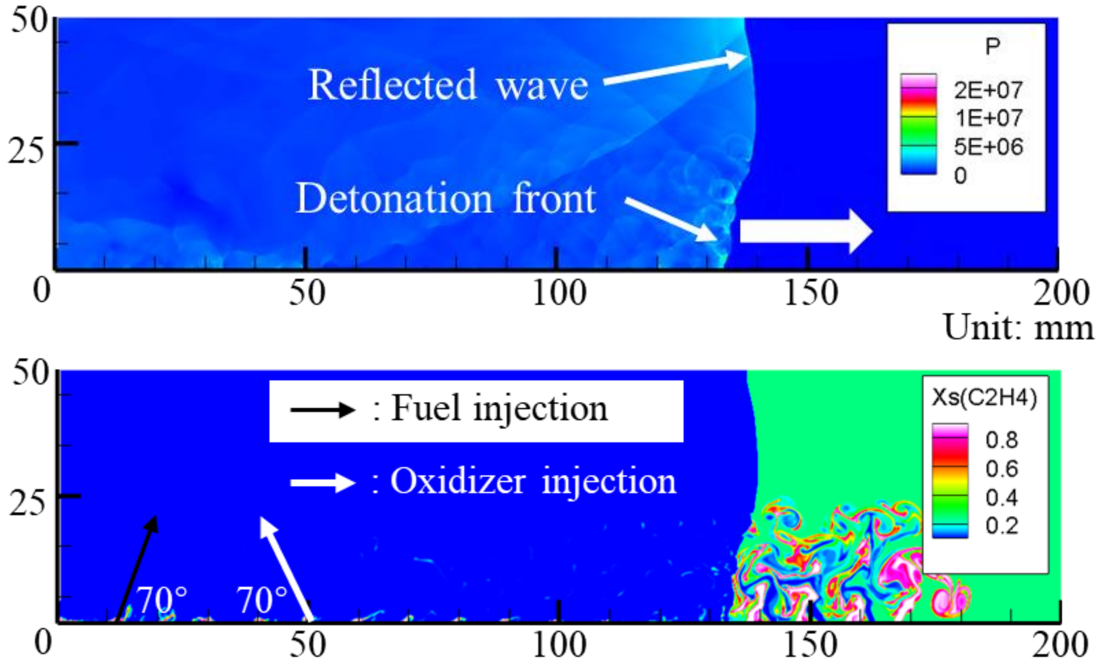
The setting of fuel injection conditions is the same as that of non-premixed fuel injection in 5.2. To keep the detonation wave propagating, a 50 kPa ethylene-oxygen premixed gas is injected into the LDC to form a partial mixed state. The numerical analysis results are shown in Table 4 and Figure 7. The injected fuel was successfully ignited, and the detonation wave was maintained and propagated. The propagation speed of the detonation wave increases with the increase of the opposite injection angle. And the opposite injection of fuel and oxidant has significantly improved the mixing and combustion of fuel compared with the vertical injection. By comparing the detonation wave propagation in the upper half of the premixed fuel and the lower half of the non-premixed fuel, when the opposite injection angle is 45 degrees, the detonation wave propagation speed in the non-premixed fuel exceeds Premixed fuel propagation speed.

Table 4 Results of detonation velocity (non-premixed gas with premixture filling).

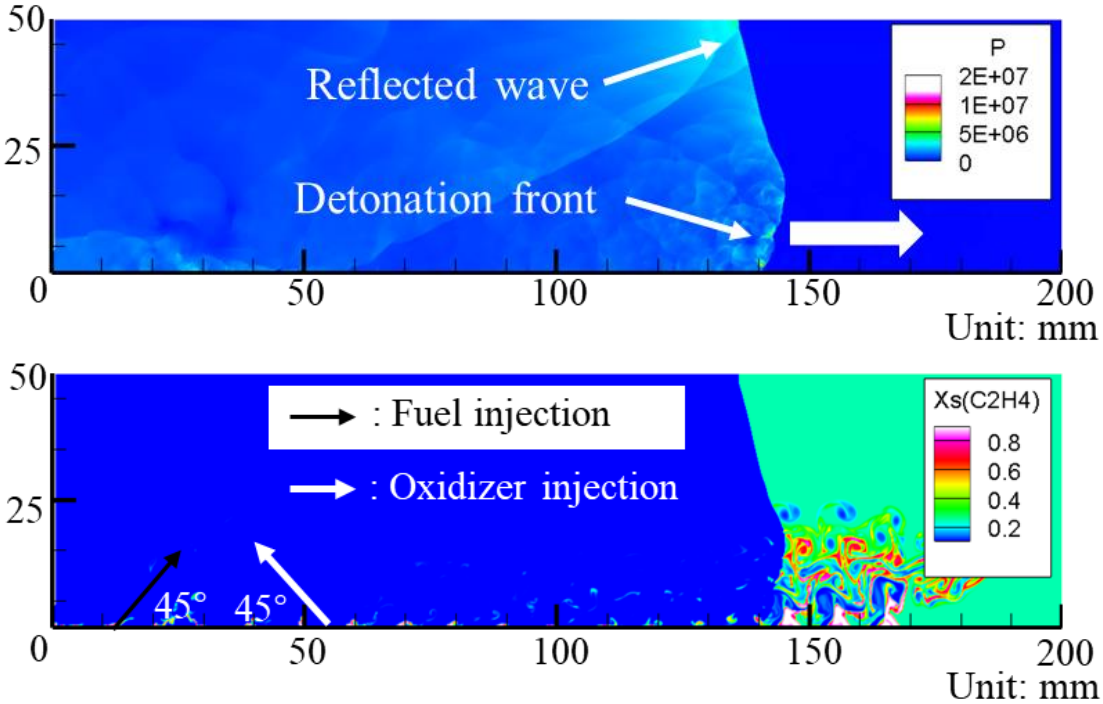
Injection port angle	90°	70°	45°
Detonation velocity	1933 m/s	2197 m/s	2317 m/s
C-J velocity		2439 m/s	



(a) Pressure distribution and fuel distribution at injection angle of 90°.



(b) Pressure distribution and fuel distribution at injection angle of 70°.



(c) Pressure distribution and fuel distribution at injection angle of 45°.

Figure 7– Numerical results of non-premixed gas injection with premixture filling.

6. Conclusions

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

After eliminating the effects of combustion chamber shape and wall loss on detonation wave propagation, 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.

Even the injection mass flow rate of the fuel is the same, the change of the injection angle will influence the propagation of the detonation wave, The fuel injection in the opposite direction of the detonation wave propagation will significantly reduce the detonation wave propagation velocity.

In the case of non-premixed injection, 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. Compared with the premixed fuel injection condition, the detonation wave propagation velocity of the non-premixed fuel under the vertical injection condition is only 79% of the C-J velocity, but after the mixing is promoted by changing the injection angle, the detonation wave propagation velocity reaches 93% of the C-J velocity. The improvement achieved with the opposite injection of fuel and oxidant is significant.

7. Acknowledgments

The authors would like to thank Dr. Shingo Matsuyama from Japan Aerospace Exploration Agency (JAXA) for assistance with the numerical analysis. This research used JAXA Supercomputer System generation three (JSS3) for numerical analysis.

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9. Copyright Statement

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