

Numerical Analysis of the Propagation of Detonation Wave Plunging Entry of a Combustible Premixed Jet Train

by

Faming WANG^{*1}, Toshiharu MIZUKAKI^{*2} and Shingo MATSUYAMA^{*3}

(Received on Mar. 16, 2022 and accepted on Jul. 7, 2022)

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 previous research using an actual RDE, due to insufficient mixing, combustion chamber shape, centrifugal force, etc., the detonation wave velocity generated in the RDE was usually significantly lower than the characteristic Chapman-Jouguet(C-J) velocity for the corresponding mixture. In this paper, to clarify the effect of detonation propagation by incomplete fuel mixing in the RDE, a linear detonation channel that simulates the RDE flow field was constructed and a numerical analysis of the propagation of detonation wave plunging entry of a combustible premixed jet train composed of ethylene(C_2H_4) and oxygen(O_2) was carried out. The numerical analysis results show that when the fuel is fully mixed with the oxidant and ignited with high energy, as the mass flow rate increases, the detonation velocity increases and approaches 92% of the C-J velocity. Compared with the 70% C-J velocity of an RDE with non-premixed fuel, the improvement is significant.

Keywords: Detonation propagation, Rotating detonation engine, Turbulent-combustion, Numerical analysis

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 many RDE-related research and have made great progress. In Japan, The 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 Center¹⁾.

Although there are many research results on RDE in various countries, propagation of the detonation 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 ratio¹⁻⁴⁾. Usually, RDE uses a non-premixed fuel injection method for safety, that results in insufficient fuel mixing. The detonation velocity generated in the RDE is usually Significantly lower than the characteristic Chapman-Jouguet velocity of the corresponding mixture, Cause

the thrust to reach the expected value, RDE has not been practical yet.

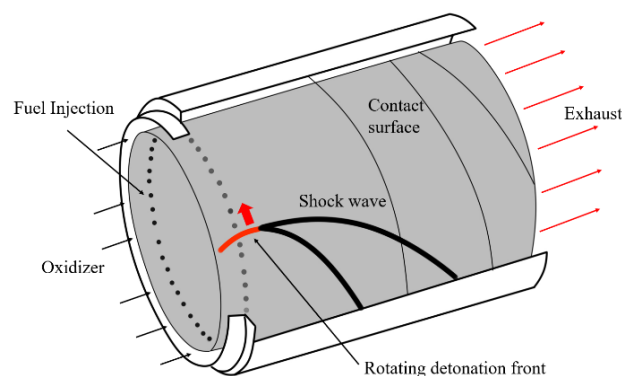


Fig. 1 Rotating Detonation Engine.

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 combustion chamber of the RDE into a linear combustion chamber to eliminate the influence of shape and centrifugal force on the propagation of detonation, so that can 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, it is first necessary to master the propagation mode of detonation wave in the completely mixed fuel. a high precision

^{*1} Graduate Student, Course of Science and Technology

^{*2} Professor, Department of Aeronautics and Astronautics

^{*3} Japan Aerospace Exploration Agency

LES of propagation of detonation wave plunging entry the combustible premixed jet train was performed by using a supercomputer system.

2. Linear Detonation Channel

The linear detonation channel facility is shown in Fig. 2. It's unfolded 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.

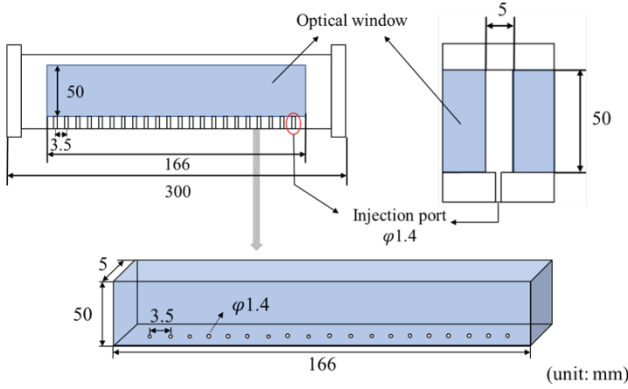


Fig. 2 Linear detonation channel.

As the injection condition of the envisioned experiment, a detonation tube filled with premixed ethylene oxygen having the same equivalent ratio as the experimental conditions is installed on the upstream side of the linear detonation channel. Detonation is generated by ignition, and the generated detonation wave enters the linear detonation channel.

3. Numerical Method

3.1 Numerical analysis code

In numerical analysis, we used JAXA's in-house code CHARIOT (Cost-effective High-order Accurate Reconstruction-scheme Intensively Optimized for Turbulent-combustion) that is designed for DNS/LES of turbulent combustion in aerospace propulsion systems⁵⁾. The governing equations of the flow used for the present LES analysis is compressible Navier-Stokes equation.

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

$$\frac{\partial \bar{\rho} \tilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j} \{ \bar{\rho} \tilde{u}_i \tilde{u}_j + \bar{p} \delta_{ij} - \bar{\tau}_{ij} + \bar{\rho} (\tilde{u}_i \tilde{u}_j - \tilde{u}_i \tilde{u}_j) \} = 0 \quad (2)$$

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

$$\frac{\partial \bar{\rho} \tilde{Y}_k}{\partial t} + \frac{\partial}{\partial x_i} \left\{ \bar{\rho} \tilde{Y}_k \tilde{u}_i - \bar{\rho} \tilde{D}_k \frac{\partial \tilde{Y}_k}{\partial x_i} + \bar{\rho} (\tilde{Y}_k \tilde{u}_i - \tilde{Y}_k \tilde{u}_i) \right\} = \bar{\omega}_k \quad (4)$$

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 126 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 , Y_s) at the cell interface. For the scalar variables (ρ , p , Y_s), 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.⁶⁾ 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.

3.2 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 models are shown in Fig. 3. 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 previous research of code validation, at a grid accuracy of 50 μm , the detonation propagation speeds duplicated the Chapman-Jouguet (CJ) velocity V_{CJ} well with very small errors less than several percent, and the error between the detonation pressure history of the numerical analysis results and the experimental value is within 10%⁷⁾⁸⁾. If the grid accuracy is increased, the triple point and cell structure will be clearer, but in the analysis of detonation engine, the influence of the cell is hardly so much on the propulsion performance⁹⁾. In this study, the detonation velocity is the main object of analysis, so it is appropriate that

the grid accuracy of this calculation is also set to 50 μm . The injection conditions for numerical analysis are shown in Table 1.

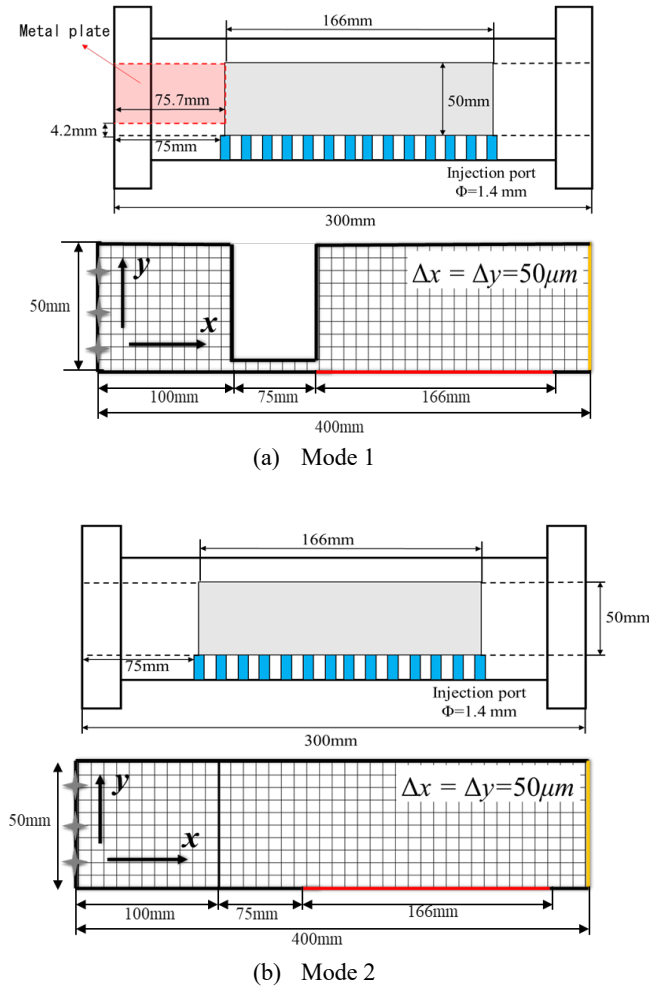


Fig. 3 Device mode with Numerical analysis model.

Table 1 Injection conditions.

Number of grid	8001x1001		
grid width	50 μm		
Fuel-oxidizer	Ethylene-oxygen premixture		
Equivalent ratio	1.0		
Filling pressure (detonation tube)	0.1 MPa		
Combustion flow path pressure	1.0 atm.		
Mass flow rate	30 g/s	60 g/s	90 g/s

4. Results and discussions

4.1 Numerical analysis results of mode 1

The numerical analysis results of Mode 1 are shown in Table 2 and Fig. 4. The detonation was successfully generated and spread. However, the difference from the expectation is that as the mass flow rate increases, the detonation velocity does not increase but decreases. The reason for this result is that when the

mass flow rate is different, the volume and height of the injected fuel are completely different (as shown in Fig. 5), so that when the detonation ignites the fuel, it consumes more energy and causes the speed to decrease.

In order to verify this idea, a more powerful ignition configuration was used. The initial detonation pressure of ignition is increased to 1.5 atm. The result is shown in Fig. 6 under the same condition of $\dot{m} = 90 \text{ g/s}$. The detonation velocity is significantly increased and reached 90% of the C-J velocity.

Table 2 Detonation velocity results of mode 1.

Mass flow rate	30 g/s	60 g/s	90 g/s
Detonation velocity	2107 m/s	1976 m/s	1833 m/s
C-J velocity	2439 m/s		

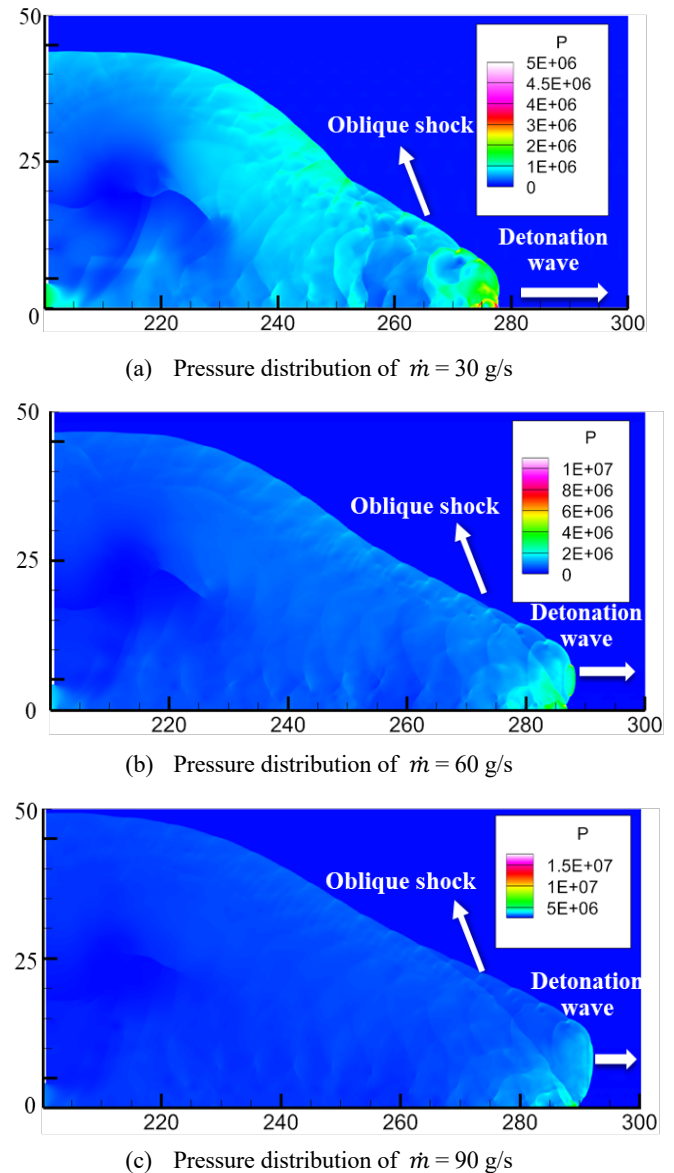


Fig. 4 Numerical analysis results of mode 1.

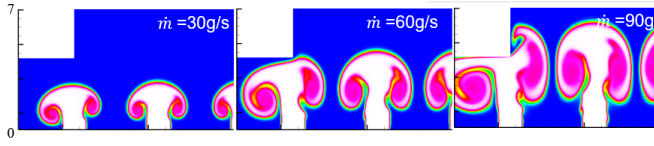
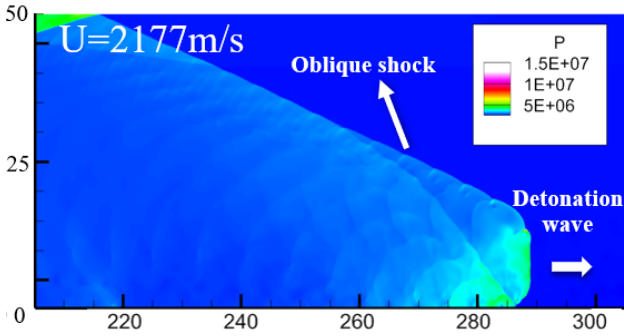


Fig. 5 Fuel injection height comparison at the same time.

Fig. 6 Pressure distribution of $\dot{m} = 90$ g/s of ignition pressure 150 kPa.

4. Numerical analysis results of mode 2

The numerical analysis results of Mode 2 are shown in Table 3 and Fig. 7. The detonation was successfully generated and propagated. With the increase of the mass flow rate, the detonation velocity gradually increased and reached about 92% of the theoretical value of C-J condition, which is a significant improvement compared with the non-premixed fuel which is usually lower than the theoretical value of 30%^[11,12].

Table 3 Detonation velocity results of mode 2.

Mass flow rate	30 g/s	60 g/s	90 g/s
Detonation velocity	1725 m/s	1979 m/s	2266 m/s
C-J velocity	2439 m/s		

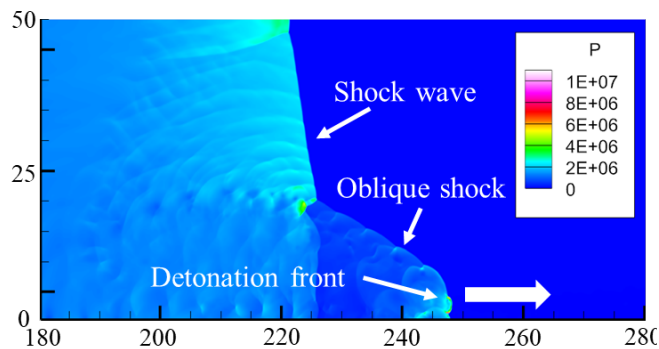
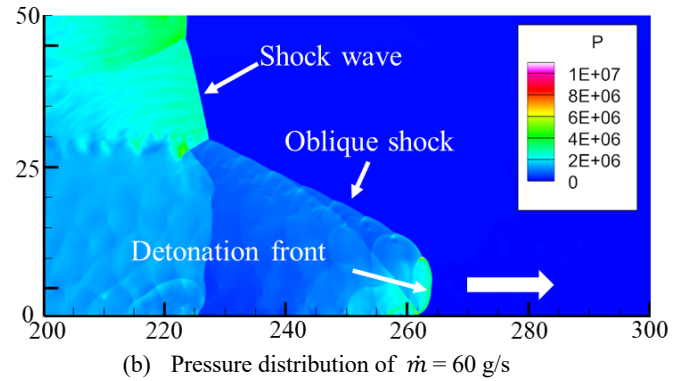
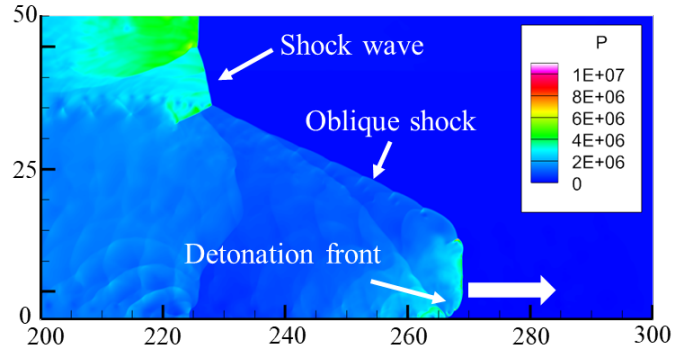
(a) Pressure distribution of $\dot{m} = 30$ g/s(b) Pressure distribution of $\dot{m} = 60$ g/s(c) Pressure distribution of $\dot{m} = 90$ g/s

Fig. 7 Numerical analysis results of mode 2.

5. Conclusions

Through the numerical analysis of the propagation of detonation wave plunging entry the combustible premixed jet train:

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 did not occur or need a longer path to reach the expected value.

With the mass flow rate increases, the detonation velocity can gradually approach the C-J velocity, and reach more than 90% of the theoretical value. Compared with the traditional RDE using non-premixed fuel injection, where the detonation velocity is only about 70% of the theoretical value, the improvement is obvious. This shows that when the fuel is completely mixed, the propagation speed of detonation is greatly improved. If the existing RDE fuel injection method can be improved to make the fuel mixing more fully, the performance of the RDE can also be improved.

Acknowledgments

For this study, we used JAXA Supercomputer System generation 3 (JSS3).

References

- 1) M. Kojima et al.: Experimental Study of Rotating Detonation Rocket Engine at JAXA. Proceedings of The 32nd International Symposium on Shock Waves, OR-04-0120 (2019).
- 2) B. A. Rankin, D. R. Richardson, A. W. Caswell, A. G. Naples, J. L. Hokes and F. R. Schauer, *Combust. Flame* 176: pp.12-22 (2017).
- 3) C. Bedick, D. Ferguson and P. Strakey, *J. Prop. Pow.* Vol.35, No.4, pp.827-837 (2019).
- 4) J. Sun, S. Liu and Z. Lin: Numerical investigation of a rotating detonation engine under premixed/non-premixed conditions. *Acta Astronaut.* Vol.152, pp.630-638 (2018).
- 5) Shingo, M., Kazuya, I., Yoshio, N., Hideyuki, T., Toshiharu, M., Makoto, K., and Hideto, K: Large-Eddy Simulation of Rotating Detonation with a Non-premixed CH₄/O₂ Injection, AIAA 2020-1174 (2020) .
- 6) Thornber, B., Mosedale, D., Drikakis, D., Youngs, D., and Williams, R. J. R., “An Improved Reconstruction Method for Compressible Flows with Low Mach Number Features,” *Journal of Computational Physics*, Vol.227, pp.4873–4894 (2008).
- 7) Faming, W., Toshiharu, M., Shingo, M. Visualization and CFD of the influence of mixing on detonation wave propagation inside a rotating-detonation engine by using linear detonation channel, AIAA 2022-1456 (2021).
- 8) Faming, W., Toshiharu, M., Shingo, M. NUMERICAL ANALYSIS OF DETONATION STRUCTURE BY USING CHARIOT. The 31st International Symposium on Transport Phenomena, p.153 (2020).
- 9) Nobuyuki, T., Koichi, A, K. Rotating Detonation Engines, *Journal of the Combustion Society of Japan*, Vol.55 No.174, pp.349-363 (2013).
- 10) Yungster. S, Radhakrishnan. K, and Perkins. H. D: Structure and Stability of One-Dimensional Detonations in Ethylene-Air Mixtures, AIAA Paper 2003-4248, E-14143 (2003).
- 11) Shingo, M: Development of Turbulent Combustion Analysis Code CHARIOT. Proceedings of The 49th JSASS Annual Meeting, 2C05 (2018).
- 12) Zhukov, V. P. and Kong, A. F: A compact reaction mechanism of methane oxidation at high pressures. *Progress in Reaction Kinetics and Mechanism*, Vol.43, No.1, pp.62–78 (2018).
- 13) Takayuki A., Keisuke Y, Youhi M, Nobuyuki T: and A. Koichi H., Numerical Analyses on Ethylene/Oxygen Detonation with Multistep Chemical Reaction, *Combustion Science and Technology*, Vol.188, No.3, pp.346-369 (2016).
- 14) Takuma, S, Stephen, V, Venkat, R: Detailed Chemical Kinetics based Simulation of Detonation-Containing Flows, Proceedings of ASME Turbo Expo 2018 Turbomachinery Technical Conference and Exposition (2018).
- 15) M. Kojima et al.: Thrust characteristics and detonation propagation behavior in Japan's largest RDRE. Symposium on Shock Waves in Japan, 2A2-1 (2020).
- 16) Shingo, M et al.: CFD Analysis on Combustion in a Rotating Detonation Combustor. Symposium on Shock Waves in Japan, 2A3-1 (2020).
- 17) Prakash, S., Fiévet, R., Raman, V., Burr, J., & Yu, K. H: Analysis of the detonation wave structure in a linearized rotating detonation engine. *AIAA Journal*, Vol.58, No.12, pp.5063–5077 (2019).
- 18) Burr, J. R., & Yu, K. H: Experimental characterization of RDE combustor flowfield using linear channel. *Proceedings of the Combustion Institute*, Vol.37, No.3, pp.3471–3478 (2019).