Relationship between fuel concentration distribution in the combustion chamber of a rotating detonation engine and its operating mode

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1 Introduction

Nowadays, the aerospace system has increasingly high requirements for thrust engines. Conventional rockets are combustion instabilities. To solve the problem of the conventional rocket engine, the rotating detonation engine become the most idea, currently. The rotating detonation engines (RDEs) are the most real of the next generator of thrust engines. The experiment research is based on two sizes of the RDE by James Koch et al. [1] who show the behavior of the rotating detonation engine. Bluemner et al. [2] have experimentally studied the mode transition of the propagation mode of rotating detonation wave (RDW) from counter-rotating waves to a single wave by measuring the pressure in the combustion chamber and the luminance of flame. Recently, a high-fidelity numerical simulation of a methane-oxygen rotating detonation rocket engine has been conducted by Prakash et al. [3], who have provided detailed insight into the mixing physics of fuel and oxidizer and have demonstrated that the high plenum pressure and injector geometry result in fairly stiff injectors against the passing of detonation waves. However, to the author's knowledge, no concentration measurements near the injector have been made to date, probably due to the difficulty of the setup of the measurement system in the annular combustion chamber of RDEs. To achieve the optimal RDEs operation mode, the fuel concentration distribution as well as the mixture of fuel and oxidizer have a decisive influence.

In this study, the fuel concentration distribution near the injector plane of the RDE combustor was measured using an infrared laser extinction method. And, the behavior of the rotating detonation engine is studied, which is based on a new optimized RDE design.

2 Experiment methods

An RDE combustor of which the outer and the inner wall is made of quartz glass was constructed for optical access. Figure 1 shows the schematic of the RDE combustor with a length of 140 mm, an outer wall diameter of 80 mm of the combustor, and a chamber width of 6 mm. The outer and inner walls of the combustor, up to 53 mm axially from the thrust wall, were made of quartz glass.

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In the present study, the fuel was methane, which absorbs an infrared laser of 3.39 μm in wavelength. Nitrogen was used as an alternative to oxygen because the present study aimed to measure the fuel concentration in non-combustion tests. Methane was supplied through 80-holes injector of 1.2 mm in diameter, while nitrogen was injected through 80-holes injector of 2.0 mm in diameter, as shown in Fig. 1. Vertical collisions of the two gases immediately after injection promotes rapid mixing.

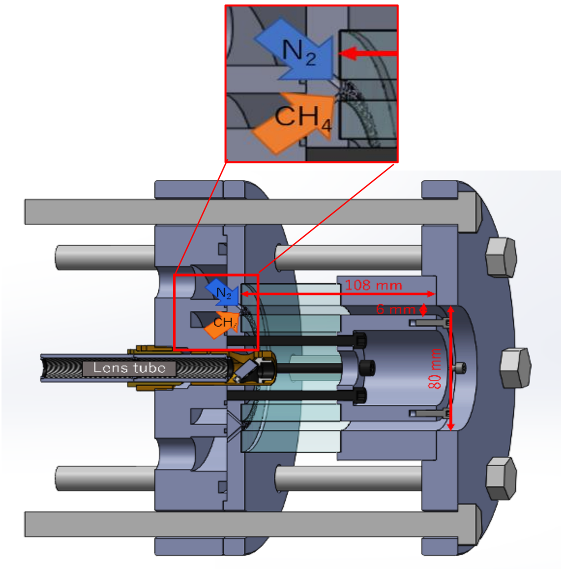


Figure 1: Schematic of RDE combustor

In operation, methane and nitrogen were at first filled into tanks at predetermined pressures and supplied to the combustor through several tubes. The feeding time of each gas was controlled with solenoid valves, and the test time was set to 326 ms considering the capacity of the tanks.

The optical setup of the infrared laser extinction method was shown in Fig. 2. The whole optical system consisting of lenses and mirrors was arranged in the lens tube shown in the photograph in Fig. 2 and was inserted into the center of the combustor. The infrared He-Ne laser with a wavelength of 3.39 μm that entered into the lens tube through the optical fiber was formed into a laser sheet by a couple of cylindrical lenses and then introduced into the combustion chamber. The transmitted laser intensity was detected using a 16-channel InAsSb photovoltaic array (Hamamatsu Photonics P15742-016DS) as shown in Fig. 3. This multichannel detector enables to measure of the circumferential fuel concentration distribution in the combustion chamber.

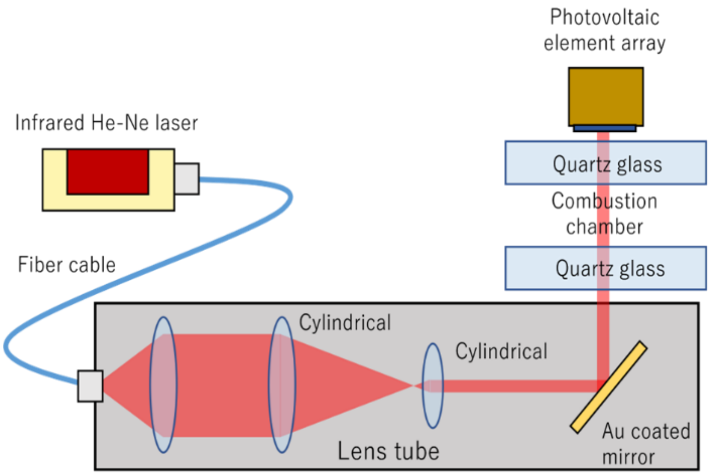


Figure 2: Optical setup of laser extinction method

From the Lambert-Beer law, the following equation holds for laser extinction [4].

$$\log_{10}\frac{I}{I_0} = - x*c*\epsilon*d \qquad (1)$$

Where I_0 is the incident laser intensity, "I" is the transmitted laser intensity, x is the mole fraction of methane, c is the total molar concentration of gas, ϵ is the molar extinction coefficient of methane, and d is the optical path length.

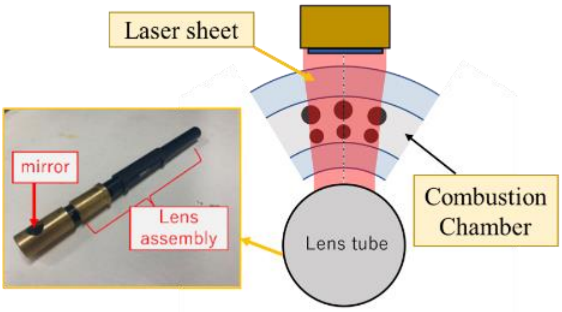


Figure 3: Measurement method of the fuel concentration distribution

3 Experiment results

3.1. Fuel concentration distribution during non-combustion.

First, the fuel concentration distribution in the combustion chamber was measured using nitrogen instead of oxygen as an oxidant. Fig. 4.a releases fuel concentration distribution at any position following the time. To make a comparison with the average value (black curve), it shows the insignificant change in the mass flow rate. It assumes that the injector gives a high-quality mixture supply.

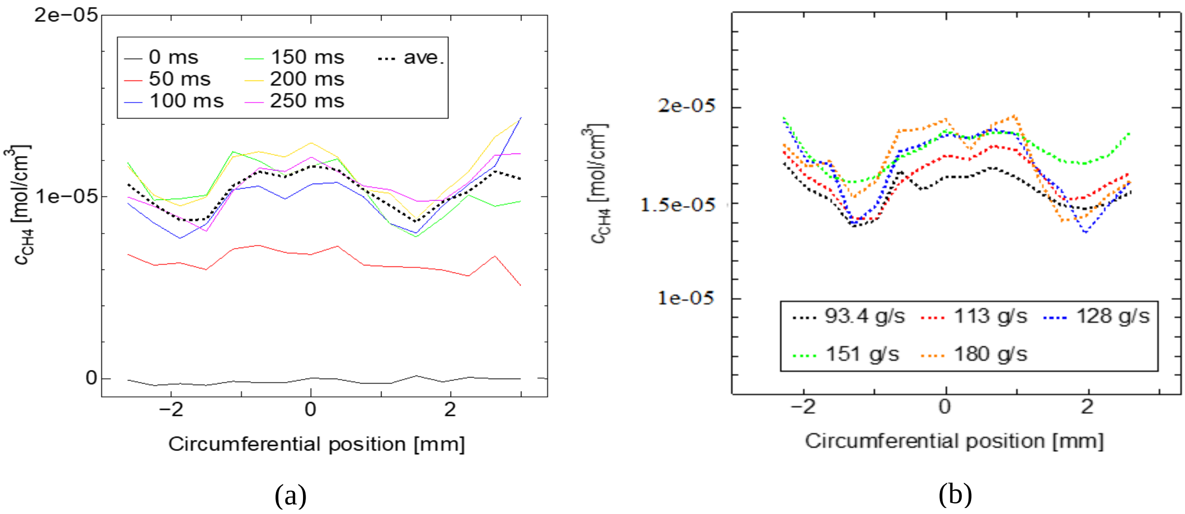


Figure 4: a) Time changes of fuel concentration $\dot{m}_{CH4}$ = 36.9 g/s distribution $\dot{m}_{N2}$ = 178 g/s; b) Fuel concentration distribution for various mass flow rate.

Fig. 4.b shows the average value of the fuel concentration distribution for each mass flow rate that was obtained after 100 ms from the start of the reactant supply. Based on the molar extinction coefficient ϵ in equation (1). The molar extinction coefficient was calculated assuming that it was equal to the density. The distance between the positions where the methane molar concentration is a minimum of about 3 mm, and although the position of the methane supply hole cannot be specified, the injector orifice distance is 2.9 mm. It turns out to be valid. In addition, there was a tendency for the molar concentration of methane to increase as the mass flow rate increased. This is thought to be due to the increase in the total gas density in the combustion chamber due to the increase in supply pressure.

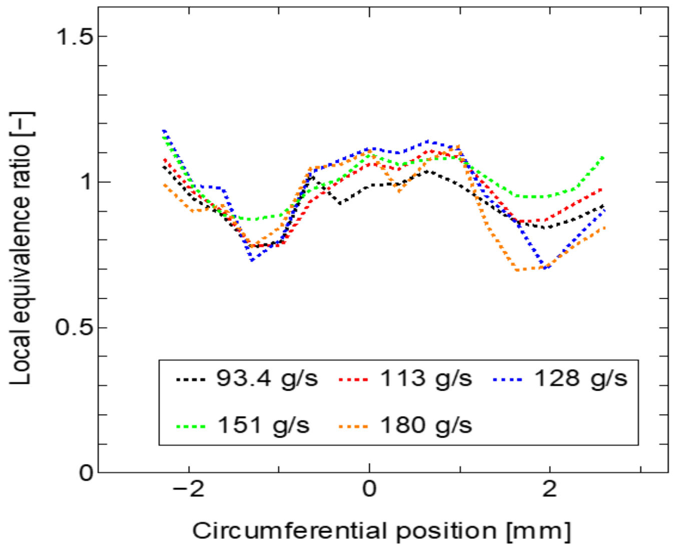


Figure 5: Local equivalence ratio for various mass flow rates.

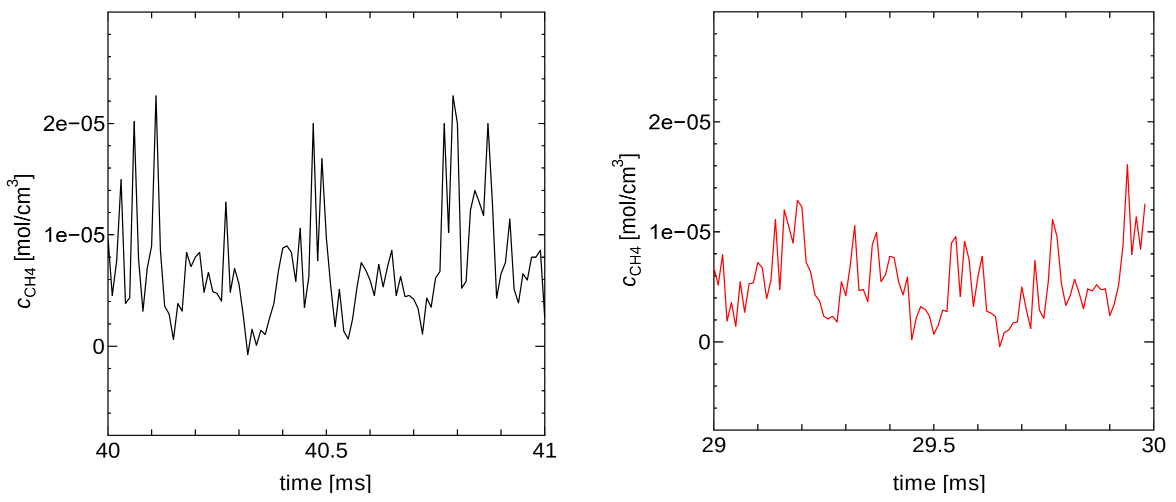
Fig. 5 shows the local equivalence ratio distribution obtained from the fuel concentration distribution and the average equivalence ratio of the entire combustion chamber. it is assumed that similar distributions appear periodically in the circumferential direction in the same way as the method for obtaining the molar extinction coefficient, Stratification of methane and nitrogen can be seen in Fig. 5, and this heterogeneity of propellant is thought to affect detonation propagation.

3.2. **Fuel concentration distribution during combustion.**

In experiment research of the RDE operation, the fuel concentration distribution measurement during combustion was performed after investigating the propagation behavior of the detonation wave in advance. In this study, we measured the mass flow rates of 117 and 73.7 g/s near the aforementioned flow rates, and the fuel concentration at 5 mm downstream from the injector. At that time, the glass part of the outer wall of the combustor was covered with a black cloth, leaving the laser light path, and a band-pass filter was placed just before the photovoltaic element array to reduce the influence of the combustion emission on the infrared laser quenching measurement.

Fig. 6 shows the temporal change of the fuel molar concentration in the combustion chamber obtained by the laser quenching method. The circumferential position of the measurement is the position where the fuel concentration is maximum, which releases in Fig. 6. In this study, the intermediate value of 1.2 $\times$ 10^5 cm^2/mol was used. In (a), the fuel concentration gradually increases and then decreases sharply, which is repeated, and the cycle is about 5 kHz. It is considered that the detonation propagates at the same velocity. In (b), the maximum fuel concentration was smaller than in (a) because the mass flow rate was small

Also, in Fig. 6, a rapid decrease in fuel concentration was observed due to the passage of the reaction zone, and the maximum value immediately before that corresponds to the amount of fuel consumed by detonation. Therefore, the average of the fuel concentration maxima at the time when the propagation behavior before and after the time shown in Fig. 7 is relatively stable was obtained at each circumferential position. However, the incident light intensity is maximum near the center of the measurement range and gradually decreases toward the outside from there. Therefore, both ends of the measurement range are shown here. It is expected that this will change the propagation behavior of detonation.



(a) $\dot{m} = 117\,\mathrm{g/s}$ (b) $\dot{m} = 73.7\,\mathrm{g/s}$

Figure 6: Fuel concentration histories in the combustion chamber.

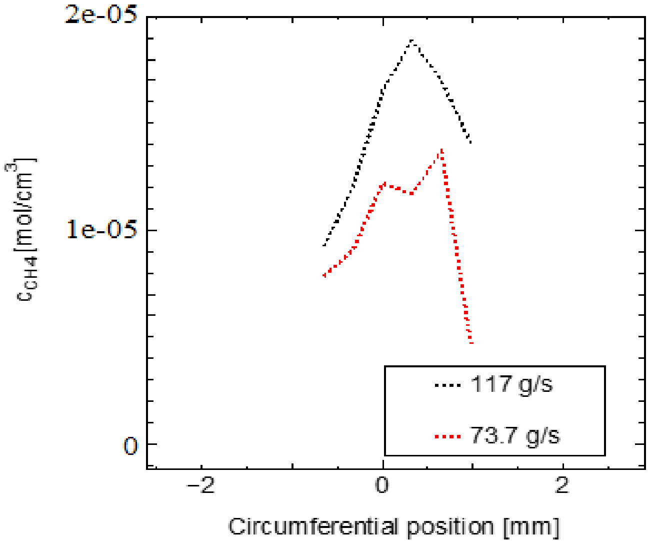
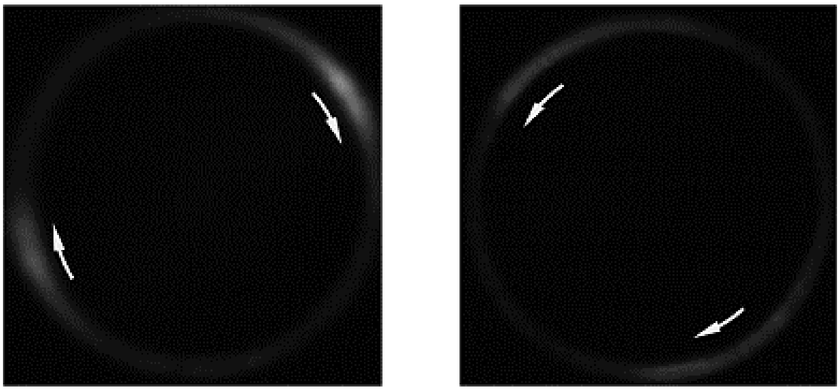


Figure 7: Fuel concentration distribution in the combustion condition

In addition, the image of the high-speed camera showed that two strong and weak combustion emissions propagated in the same direction or the opposite direction, and it was found that each propagated at 5 kHz. Images taken by the high-speed camera are shown in Fig. 8. In (a), the detonation was easily maintained because the flow rate was large, and the two detonations propagated stably in the same direction. On the other hand, in (b), the flow rate is low, and not enough reactants are supplied to maintain detonation, so the mode becomes unstable and the deflagration accompanied by two compression waves rotates in opposite directions. Since the behavior was unstable at the flow rate of (b), it was also observed that the disappearance and appearance of the combustion luminescence were repeated frequently.



(a) $\dot{m} = 117\,\mathrm{g/s}$ (b) $\dot{m} = 73.7\,\mathrm{g/s}$

Figure 8: The captured image of detonation propagation

4 Conclusion

The fuel concentration distribution measurement system in the RDE combustion chamber was constructed using the infrared laser quenching method, and the methane concentration distribution in the RDE combustion chamber was experimentally investigated. As a result, the methane concentration distribution with the same period as the circumferential arrangement of the fuel injector holes was obtained, and the circumferential distribution of the methane local equivalence ratio was obtained. In addition, the time change of the fuel concentration during combustion was obtained, and the frequency of the change was the same as the frequency of the combustion chamber pressure

5 Acknowledgement

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