Effect of linearly increased equivalence ratio on combustion instability of lean-premixed low-swirl hydrogen jet flame

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1 Introduction

As an eco-friendly combustion method, lean-premixed hydrogen combustion is attracting attention since lean-premixed hydrogen combustion has the advantage of significantly reducing NOx emissions and emitting no CO_2. However, the lean condition is particularly prone to combustion instabilities (CI), and CI can cause severe damage to combustors. Many studies have investigated CI in various systems and conditions, but the details of CI's occurrence conditions and amplification characteristics are not fully understood.

Under these circumstances, an experimental study on CI in lean-premixed hydrogen combustion in a low-swirl combustor (LSC) was conducted by Shoji *et al.* [1] in Japan Aerospace Exploration Agency (JAXA). In that experiment, unique periodic flame fluctuations were observed for the first time and induced CI by coupling with pressure fluctuations. However, the detailed mechanisms have not been fully elucidated due to the difficulty of performing detailed measurements and investigations in the experiment. In order to investigate the more detailed characteristics of the CI in the LSC, a Large-eddy simulation (LES) was conducted by Nagao *et al.* [2]. That numerical simulation succeeded in accurately reproducing the temporal fluctuations of the flame structure and the characteristics of the pressure oscillation observed in the experiment. In addition, in the numerical study, sporadic decay of pressure oscillation was observed, and it was concluded that the aperiodic flame transformation was responsible for the sporadic decay. However, the numerical study presumed that the equivalence ratio of the inflow is constant, whereas the experiment linearly increased the equivalence ratio with time. Consequently, the influence of the time variation of the equivalence ratio on the CI is yet to be clarified in the numerical study.

Therefore, this study investigates the effect of the time variation of the equivalence ratio on the CI in the LSC by linearly increasing the equivalence ratio with time in a single LES. Specifically, the equivalence ratio is increased linearly from 0.3 to 0.5 in 0.4 s.

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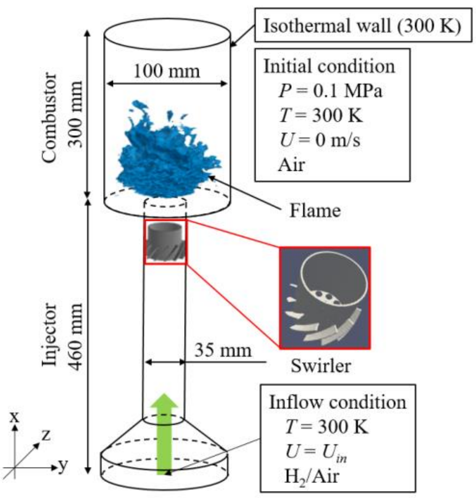

Figure 1: Schematic of computational domain and conditions.

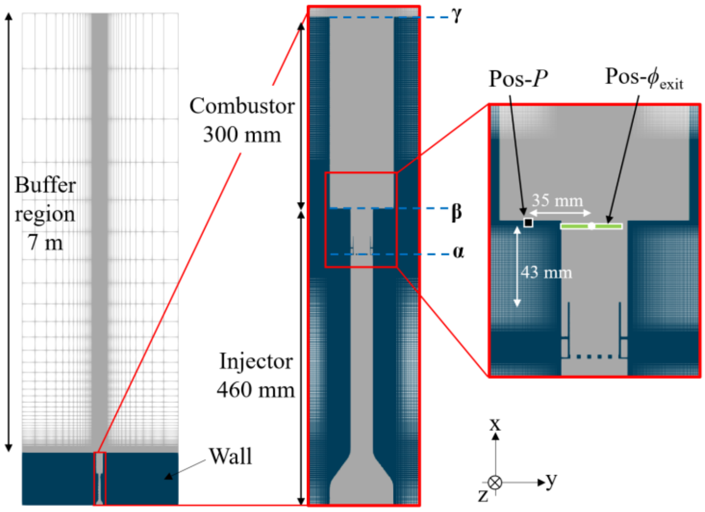

Figure 2: Computational grid of LES.

2 Numerical methods

2.1 Governing equations

The governing equations are the Favre-filtered form of the conservation equations of mass, momentum, enthalpy, and mass fraction of chemical species, along with the equation of state for ideal gas. As a sub-grid scale model, Dynamic Smagorinsky Model [3] is used, and as a turbulent combustion model, Dynamically thickened flame model [4-7] is employed. As a reaction model for hydrogen/air gas, the detailed reaction mechanism proposed by Miller and Bowman, which considers nine chemical species and 20 reactions [8], is used.

2.2 Computational setups

This LES is performed using the in-house code FK^3 [9,10]. Figure 1 shows the schematic of the computational domain just around the combustor system and conditions for LES, and Fig.2 illustrates the entire computational domain and grid distribution. The configuration of the combustor is set to recreate the experimental setups [1]. The inflow velocity is set to maintain the incoming mass flow rate of the premixed gas. The equivalence ratio at the bottom of the injector is increased linearly from 0.3 to 0.5 in 0.4 s. The sampling positions of pressure and the equivalence ratio which is averaged at the injector exit plane ϕ_{exit} are also shown in Fig.2.

3 Results and discussion

To observe the time variation of pressure oscillation with the increasing equivalence ratio, Fig.3 shows the time series of the pressure and the spatially averaged temperature in the combustor T_{ave}. In this figure, the spatially averaged temperature in the combustor $T_{ave,ref}$ at the case with constant equivalence ratio of 0.39 [2] where the stronger pressure oscillations were observed is also shown.

As this figure shows, the pressure oscillates weakly at $t < 0.4$ s, and begin to be amplified at $t > 0.4$ s. Moreover, T_{ave} increases with the increasing ϕ_{exit} and T_{ave} exceeds $T_{ave,ref}$ at around $t = 0.4$ s, the time when the pressure oscillations begin to be amplified, as pointed out by the black arrow. At this time, the

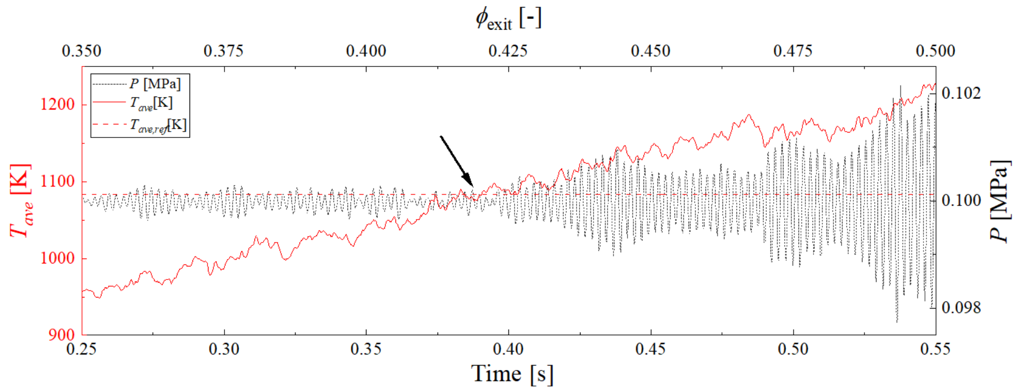

Figure 3: Time series of spatially averaged temperature in combustor T_{ave} and pressure P.

oscillation mode conincides with the mode in the case with constant equivalence ratio because the oscillation mode of pressure mainly depends on the combustor comfiguration and the temperature in the combustor.

To evaluate the characteristics of the pressure oscillations in detail, the power spectra of the pressure fluctuations are compared between the LESs and the experiment. The peak frequency of pressure oscillations in this numerical study is 412 Hz. In the previous study, the peak frequency was 403 Hz in the experiment [1] and 370 Hz in the numerical simulation [2]. These are the longitudinal three-quarter wave mode for the entire combustor system, and despite the slight difference among each peak frequency, they are the same oscillation mode.

To investigate the correlation of oscillations of the pressure and the heat release rate, Fig.4 shows the local Rayleigh Index (*RI*) distributions on the *x*-*y* plane (z = 0 mm) at different time instances. In this study, the *RI* is defined below and the positive and negative values of *RI* indicate that correlation of oscillations of the pressure and the heat release rate is strong and weak respectively.

$$RI = \frac{1}{t_s}\int_{t_0}^{t_0+t_s} \frac{P'q'}{|P'|_{ave}|q'|_{ave}}dt$$

Here, P' and q' are the fluctuations of pressure, and the heat release rate, respectively. $|P'|_{ave}$ and $|q'|_{ave}$ are the time averaged absolute value of P' and q'. The sampling time t_s is set to 0.050 s and t_0 is the lower limit of integration. As shown in Fig.4, at the time when pressure oscillations are weak (e.g. t_0 = 0.25 s, 0.30 s), large negative value of RI is distributed at 10 mm < x < 40 mm and $|y|$ < 30 mm (circled in white in Fig.4 (t_0 = 0.25 s)), indicating that the oscillation of pressure and heat release rate negatively correlate in this region. Also, at the time when the strong pressure oscillations are observed (e.g. t_0 = 0.45 s, 0.50 s), a large positive value of RI is distributed at 20 mm < x < 40 mm and 20 mm < $|y|$ < 40 mm (circled in white in Fig.4 (t_0 = 0.50 s)), indicating that the oscillation of pressure and heat release rate positively correlate in this region.

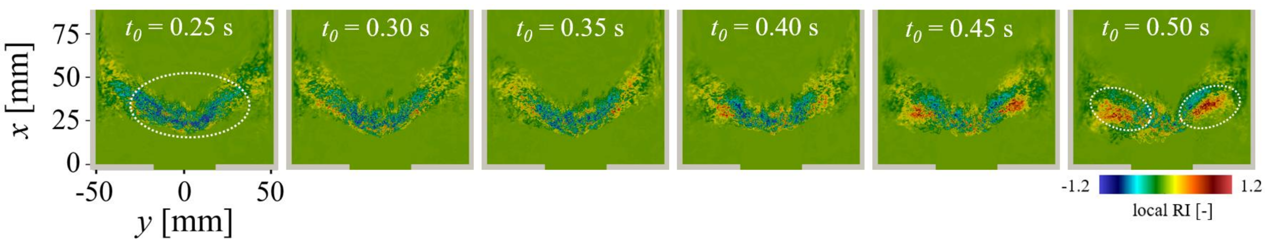

Figure 4: Sequential images of local *RI* distribution on *x*-*y* plane (z = 0 mm).

4 Conclusions

In this study, the effect of the linearly increased equivalence ratio on the combustion instability in the low-swirl combustor was investigated by using the Large-eddy Simulation. The results showed that the amplitude of the pressure oscillations increased significantly when the spatially averaged temperature inside the combustor reached a certain temperature. This temperature was the same as the spatially averaged temperature in the case with a constant equivalence ratio (0.39), where a larger amplitude was observed in the previous numerical study. At this temperature, the wavelength is approximately three-quarters of the entire system, which was also observed in the experiment.

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