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Unsteady Reynolds-Averaged Navier-Stokes Simulation of Axial and Radial Instability in A High Mixing Ratio H_2/O_2 Rocket Engine with A Shear Coaxial Injector

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Abstract - This study investigates the axial and radial combustion instability in a high mixing ratio H_2/O_2 rocket engine with a shear coaxial injector using Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations. The combustion is modeled using the N-S equations with a chemical reaction source and the Curran chemical reaction model, while turbulence is modeled using the SST k-ω model. The analysis emphasizes the evolution of vortex structures and the fluctuation characteristics of pressure, temperature, H2O, and OH mass fractions. Key findings include the observation that vortex structures are most prominent during the initial doping process and gradually dissipate afterward. Pressure fluctuations are significant at the low frequency at the nozzle inlet and outlet, while temperature, H_2O, and OH exhibit more pronounced fluctuations at 125 mm from the injector. Phase differences between the nozzle inlet and other positions reveal negative correlations at the high frequency, particularly at 225 mm from the injector. These insights provide valuable information for improving the design and stability of H_2/O_2 rocket engines.

Keywords: Combustion instability, H_2/O_2 rocket engine, URANS simulation, shear coaxial injector, vortex structure.

1. Introduction

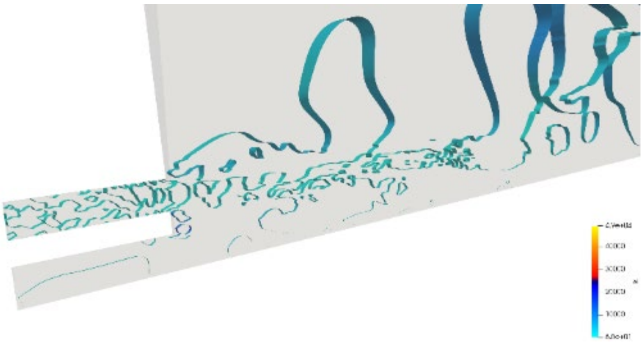
H_2/O_2 rocket engines play a key role in space propulsion. Numerous studies have been focused on the combustion efficiency [1], stability [2], and the effect of the injector [3] of H_2/O_2 gas generators. For a H_2/O_2 rocket engine, numerical simulation can effectively model the combustion process [4]. Conaire et al. successfully captured the ignition interface using a chemical reaction model [5]. However, few studies have been conducted on the axial and radial instability of large mixing ratio hydrogen-oxygen engines, especially those using shear coaxial injectors, when shear instability exacerbates this instability. The aim of this study is to analyse the combustion instability of an oxygen-enriched gas generator in a hydrogen-oxygen engine and to provide guidance for subsequent engine design.

2. Methods

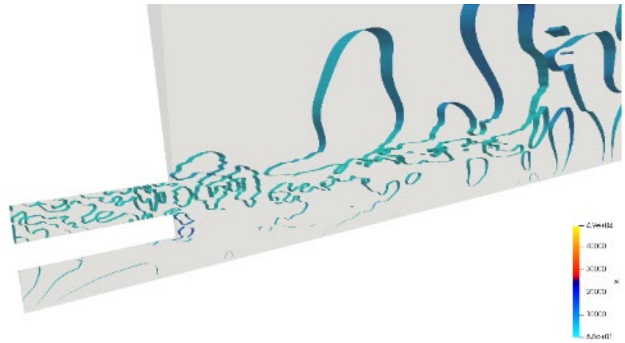
In this study, the N-S equation containing a chemical reaction source term and the ten-component, twenty-one-step Curran chemical reaction model were used.The turbulence model is modelled using the SST k-ω model, the time advance is in PIMPLE, and the Gauss linear method containing a limiter is used for the gradient and convective term of the velocity field.

3. Results

The Q coutour for 130ms and 150ms are shown in Fig. 1. It can be observed that the vortex structure is most obvious during the doping process, after which the vortex gradually dissipates.

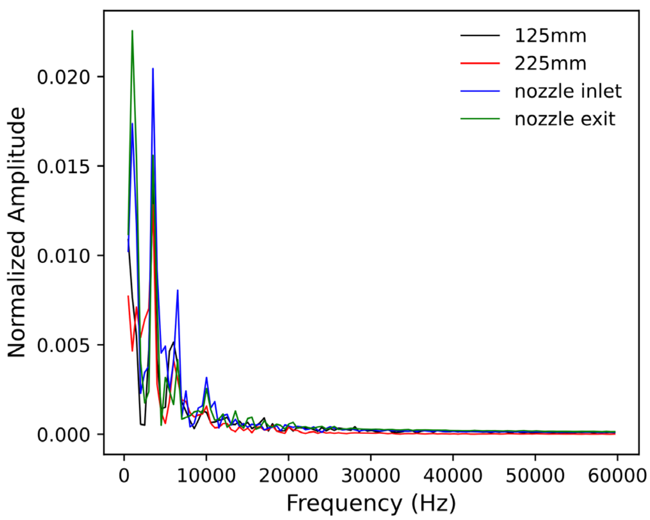


(a) 130ms

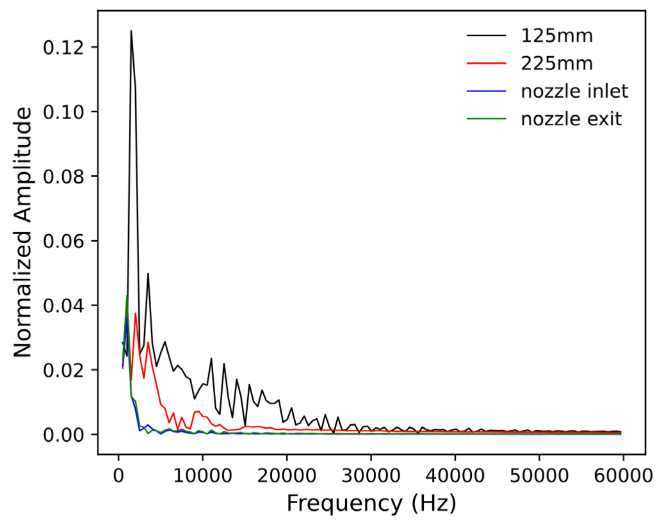


(b) 150ms

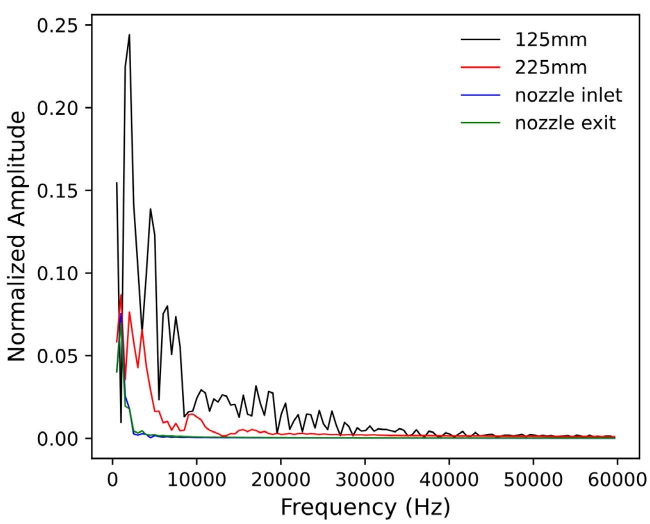
Fig. 1: Q coutour at different moments



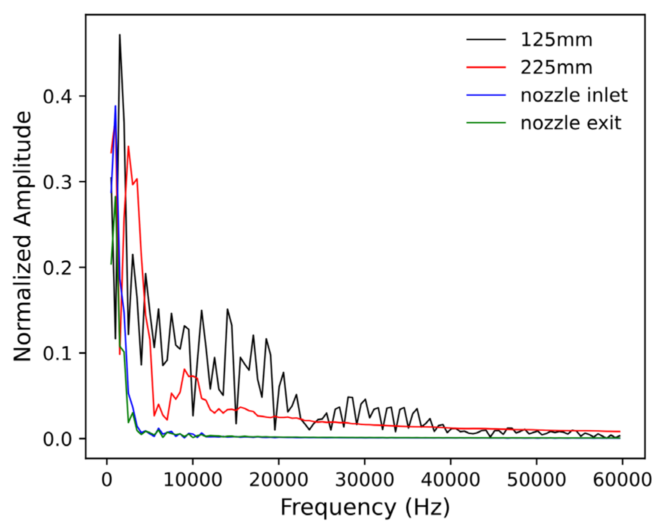
(a) Pressure



(b) Temperature



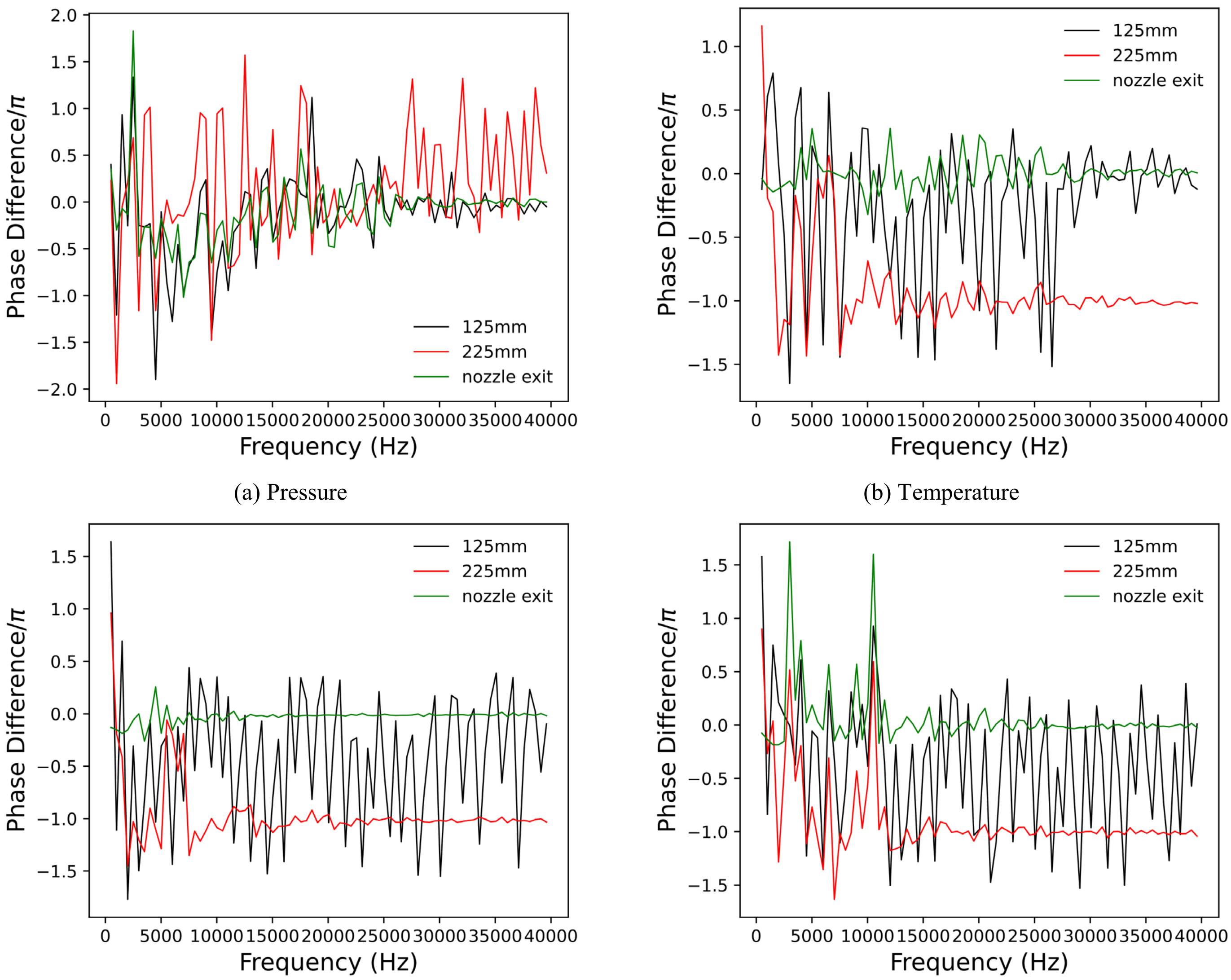
(c) H_2O



(d) OH

Fig. 2: Amplitude Spectrum

The results after applying FFT and normalisation to the combustion flow field data from 130 ms to 160 ms at 125 mm and 225 mm from the injector as well as at the nozzle inlet and nozzle outlet are shown in Fig. 2. It can be seen that the pressure fluctuations at the nozzle inlet and nozzle outlet are large at the low frequency, but the temperature, H_2O, and OH do not fluctuate so significantly. The fluctuations of temperature, H_2O, and OH at 125 mm from the injector were significantly larger than those at the other three locations, and the fluctuation bands were also significantly wider than those at the other three locations.



(a) Pressure

(b) Temperature

(c) H_2O

(d) OH

Fig. 3: Compared to the phase difference at nozzle inlet

The phase difference compared to the other three positions of the nozzle inlet plotted from the FFT data is shown in Fig. 3. It can be seen that the phase difference between the nozzle outlet and the nozzle inlet is close to zero at the high frequency for temperature, H2O and OH. The phase at 225 mm from the injector is basically negatively correlated with that at the nozzle inlet, which is reflected as the opposite phase at the high frequency. The phase at 125 mm from the injector shows mostly negative correlation with the nozzle entrance, and the phase difference at the high frequency continues to oscillate significantly.

4. Conclusion

In this study, the combustion instability in the axial and radial and the decay characteristics of fluctuations in the combustion flow field in a rocket engine with a high mixing ratio of H_2/O_2 are analysed by URANS simulations. The main findings include:

1. The vortex structure is most prominent during the doping process and gradually dissipates afterward, as observed in the Q contour at different times.

2. Pressure fluctuations at the nozzle inlet and outlet are significant at the low frequency. However, temperature, H_2O, and OH do not exhibit such pronounced fluctuations.

3. At 125 mm from the injector, the fluctuations in temperature, H_2O , and OH are significantly larger and cover a wider frequency band compared to other locations (225 mm from the injector, nozzle inlet, and nozzle outlet).

4. The phase difference between the nozzle outlet and inlet is minimal and approaches zero at the high frequency. The phase at 225 mm from the injector is negatively correlated with that at the nozzle inlet, showing opposite phases at the high frequency. The phase at 125 mm from the injector also shows a negative correlation with the nozzle inlet, with significant oscillations in the phase difference at the high frequency.

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