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Effects of convection time on the high harmonic combustion instability in a partially premixed combustor

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Abstract

The fuel composition effects of H_2/CH_4 syngas in a partially premixed model combustor (PP-MC) were examined for the unique phenomenon of combustion instability (CI) frequency/mode shifting (FMS), which is a transition of mode as well as frequency. The increase in the H_2 composition of the fuel altered FMS from a longitudinal fundamental mode (≈250 Hz) to a 7th harmonic mode (≈1750 Hz). The cause and characteristics of this FMS were investigated using OH planar laser-induced fluorescence (OH-PLIF) measured at 10 Hz, particle-image velocimetry (PIV), and the flame transfer function (FTF).

The convection time (τ_{conv}) was assumed to be the key parameter of the FMS. Thus, tests were conducted to determine the air flow rate ($\dot{V}_{air}$) and equivalence ratio (φ) variation, which are vital parameters of the τ_{conv} in terms of the flame length and mixing time. The φ variation caused obvious changes in the flame length and instability frequency/mode, while the $\dot{V}_{air}$ variation did not. The τ_{conv} was analyzed by calculating the global convection time (τ_{conv_global}) and the real convection time (τ_{conv_real}) from the length of the OH-PLIF-based unburned mixture length divided by the averaged mixture nozzle exit velocity. The τ_{conv_real} was calculated from the integral of the real velocity determined from PIV. Both calculations showed an inverse correlation between τ_{conv} and CI frequency, which particularly signifies that the FMS is controllable and a specific mode of CI can be generated by adjusting the τ_{conv}. The FTF was measured to determine the intrinsic characteristics

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of the flame. The FTF phase was normalized by the Strouhal number (St) and identified a direct relationship between FTF gain and τ_{conv} variation.

In conclusion, the τ_{conv} is the main reason for the FMS. The importance of τ_{conv} in understanding the CI characteristics was confirmed in a PP-MC using high H_2 fuels.

Keywords: Partially premixed model combustor; Combustion instability; Convection time; OH-PLIF; Flame transfer function

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1. Introduction

Research on combustion instability (CI) has been ongoing since it was first described in the early development of space propulsion engines and later in dry low-NO_x gas turbines. For the past three decades, a better understanding of the CI mechanisms has been obtained from many studies on time-lag analysis [1,2], flame/vortex interactions [3], processing vortex core [4–5], swirl number fluctuations [6], and interference between acoustic and convective disturbances [7]. Improvements in measurement techniques, such as high-repetition rate planar laser-induced fluorescence (PLIF), have provided a deeper understanding and have facilitated the quantification of information about continuous flame behavior [8,9].

However, these studies have been conducted primarily using lean premixed combustors, whereas recent interest in fuel diversification and global warming has shifted the combustion concept from fully premixed to partially premixed types. The partially premixed combustion concept is preferred, as it achieves the mutual benefits of anti-flashback and NO_x reduction because the new fuels, such as biomass, synthetic natural gas (SNG), and syngas derived from coal or wastes, contain considerable amounts of H_2. Allison et al. [10], who utilized a partially premixed model combustor (PP-MC) at the German Aerospace Center to investigate syngas and hydrocarbon fuels (methane, propane, and ethylene), found that the CI frequency varied according to the fuel (i.e., when the flame speeds were matched, a similar CI frequency was found). Lee et al. [11] observed a shifting phenomenon in both the instability frequency and mode with increases in the H_2 composition, and they suggested a new time scale of skewness for the precise application of a time-lag analysis in a PP-MC.

The CI frequency/mode shifting (FMS) phenomenon was also found during the airflow rate variation in a premixed natural gas combustor [12]. However, most researchers [12–15] have either reported FMS only phenomenologically or the FMS phenomenon was not the main topic. Therefore, the present study was conducted to investigate the characteristics of FMS, as well as to identify the reason for FMS from the longitudinal fundamental mode to other modes. The new aspects of the work presented here are the following:

The fuel composition, airflow rate ($\dot{V}_{air}$), and equivalence ratio (φ), variables that can change the convection time (τ_{conv}), were selected, and the relationship between FMS was verified in a PP-MC. The global convection time (τ_{conv_global}) was calculated based on the OH-PLIF and the fuel injection velocity. The flame length or center is normally used for the τ_{conv} calculation [11,16]; however, the unburned mixture length was used in this research to satisfy the definition of the τ_{conv}. The real convection time (τ_{conv_real}) was also calculated from the particle-image velocimetry (PIV) measurement, and it was well matched with the τ_{conv_global} variation trend. The previous flame transfer function (FTF) research used a narrow modulation frequency range and was mainly conducted in a premixed combustor [17–19]. The present study employed a wide range of modulations (0–1000 Hz), and the effects of τ_{conv} at the FTF were determined by varying the fuel composition, $\dot{V}_{air}$, and the φ.

2. Experimental apparatus

Figure 1 shows the atmospheric PP-MC used for this study. The combustion air at 200 ± 5 °C, which was controlled by a mass flow controller (MFC) (Bronkhorst, F-206BI, uncertainty = ± 0.8%), was supplied by a central annular swirling nozzle (inner diameter = 25 mm, outer diameter = 40 mm, 14 swirl channels, swirl number = 0.832), and 90%

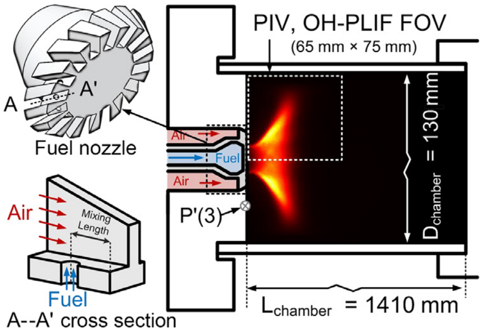

Fig. 1. Schematic diagram of the PP-MC.

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