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Proceedings of the Combustion Institute 35 (2015) 3263–3271

Proceedings of the Combustion Institute

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Investigation into the cause of high multi-mode combustion instability of $H_2/CO/CH_4$ syngas in a partially premixed gas turbine model combustor

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Available online 30 July 2014

Abstract

In this paper, the fuel composition effects of $H_2/CO/CH_4$ syngas (0–100% for each component gas) on the self-excited high multi-mode (mainly the 3rd and 4th with their harmonics) combustion instability (CI) characteristics have been studied in a partially premixed swirl-stabilized gas turbine model combustor by investigating phase-resolved high-speed OH^* planar laser induced fluorescence (OH-PLIF) and OH^* chemiluminescence at a rate of 12.5 kHz and analyzing the proper orthogonal decomposition (POD), spatio-temporal Rayleigh index (RI), and time-lag. Phase-synchronized OH-PLIF images suggested critical clues of CI driving mechanisms, including the periodic alternation of flame attachment/detachment and vortex coupling with everlasting flames at the outer recirculation zone due to high hydrogen fuels' high reactivity. These PLIF results also demonstrated that the relatively short mixing length and highly fuel-dependent flame length are the root causes of a high instability-mode and sensible mode-shift. Thus, PLIF images were used to calculate the flame length by obtaining the intensity-weighted centroid for the more precise time-lag analysis. The spatio-temporal RI results indicated that the fuel composition affects the location and intensity of CI driving/damping, RI frequency, and instability mode and frequency. POD analysis from high-speed OH^* images showed that the distinct coherent structures and large roll-up of flames are responsible for generating flame oscillations for each mode. High cross-correlation between the POD modes showed the convection of these coherent structures and axially-alternative swirl-like flame motions. At some particular compositions of $H_2/CH_4/CO$, high multi-mode CI was observed (e.g., the 3rd, 4th, and 6th modes appear simultaneously) and the original time-lag model could not be applicable, since the acoustic pressure wave is not simply sinusoidal but largely distorted. Thus, a new time-lag model using

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http://dx.doi.org/10.1016/j.proci.2014.07.013

skewness time (τ_{skew}) was proposed to reflect the distortion from multi-mode CI and the accuracy of this model was verified using the experimental data.

Keywords: High multi-mode combustion instability; Synthetic gas combustion; Partially premixed flame; Proper orthogonal decomposition; Time-lag analysis

1. Introduction

Many studies have been conducted on combustion instability (CI) in a lean-premixed gas turbine model combustor (LPM-GTMC) over the past several decades. Much knowledge has been gained regarding CI mechanisms, including the continuous feedback of oscillations among acoustic pressure, equivalence, and heat release (p', φ', and q') [1]; flame/vortex interaction [2]; entropy perturbation [3]; processing vortex core [4]; interference between acoustic and convective disturbances [5]; and temporal swirl strength fluctuations [6]. Furthermore, with advances in optic measurements such as high-repetition high-power lasers, high-speed intensified cameras, and their utilizing technics, new findings on high-speed interactions between flames and flow have been reported [7], and useful CI analysis methods, including proper orthogonal decomposition (POD) [8], time-lag analysis [9], flame transfer/describing functions [10,11] and spatio-temporal Rayleigh index (RI) [12], have been introduced and gradually progressed. However, there remains a subject of great interest and some controversy regarding the CI mechanisms, since it is impossible to derive a universal mechanism for the interpretation, control, and prediction of complex unsteady combustion physics, and the application of CI mechanisms can vary for combustor geometry, combustion methods, and fuels.

Recently, with increasing concern regarding the integrated gasification combined cycle and synthetic natural gas, new CI characteristics of $H_2/CO/CH_4$ syngas have been reported [8,12–14]. Some of them have been conducted in a flashback-easy LPM-GTMC, so limited results on high hydrogen content fuels have been published. Otherwise, a partially premixed GTMC (PPM-GTMC) [12] or low swirl injector [8] was utilized to investigate CI characteristics of high hydrogen content syngas in a flashback-free condition.

The new aspects of the present work differentiated from other syngas CI research are as follows.

(1) The effect of fuel composition on CI was investigated using the PPM-GTMC for the H_2, CO and CH_4 content from 0 mol% to 100 mol%, respectively, while most other researchers reported syngas results up to 90 mol% of H_2 (Davis, $\leqslant$90 mol% [8]; Allison, $\leqslant$45 mol% [12]; Dodo, $\leqslant$65 mol% [13]; Hasegawa, $\leqslant$30 mol% [14]). In particular, it is well known that it is difficult to visualize CO flames in a GTMC due to carbonyl contamination at the quartz combustor wall, preventing laser diagnostics [15]. To overcome this problem, a cold trapper was implemented by immersing condensation coils in a −30 to −60 °C alcohol bath; then, the flame was clearly visualized even at a high CO content by eliminating carbonyls in fuel.

(2) $H_2/CO/CH_4$ syngas flames generated the self-excited high-mode CIs at 750 Hz and 1000 Hz frequencies, which correspond to the 3rd and 4th longitudinal modes, respectively. To determine the reason for these non-fundamental high mode CIs and to analyze them, measurements were taken of phase-resolved high-speed OH^* planar laser induced fluorescence (OH-PLIF) and OH^* chemiluminescence, and analysis techniques, including POD, spatio-temporal RI, and time-lag, were applied.

(3) For particular compositions of $H_2/CH_4/CO$, multi-mode CI was observed (e.g., the 3rd, 4th, and 6th modes appear simultaneously), as previously reported phenomena of self-excited multi-mode CI [16] or the transition from fundamental to higher harmonics [17]. In these cases, the original time-lag model with a thin flame assumption or decomposition to a single mode is not valid since p' is not simply sinusoidal but largely distorted. Thus, a new time-lag model using τ_{skew} was proposed to reflect the multi-mode distortion; then, this model's accuracy was verified using the experimental data.

2. Experimental apparatus

The PPM-GTMC, shown in Fig. 1, was used to study syngas CI. To meet gas turbine relevant conditions, combustion air at 356 ± 5 °C controlled by a mass flow controller (Bronkhorst F-206BI, uncertainty = ±0.8%) was supplied to the flame through a central annular swirling nozzle (swirl number = 0.832, 14 swirl channels, i.d. = 25 mm, o.d. = 40 mm). Tests were conducted at a slightly elevated pressure (1.1–1.4 bar), since a 90% area of the combustor outlet