Influences of axial-fuel-staging on combustion dynamics of a lean premixed combustor

Yongseok Choi, Kyu Tae Kim
Department of Aerospace Engineering, Korea Advanced Insttitue of Science and Technology
291 Daehak-ro, Yuseoung-gu, Daejeon, 34141, Republic of Korea

1 Introduction

Driven by the demand for increased energy efficiency and emissions regulations, gas turbine manufacturers are continuously stimulated to introduce new combustion techniques in their combustors, such as lean-premixed combustion which is a promising technique for improving efficiency and emissions[1-3]. Despite technological advancements in gas turbine combustor, improved NOx emission control strategies need to be further required to meet the more strigent NOx emission standards and its dependency on temperature and residence time[4-6]. Combustor design, here, plays a crucial role in achieving these goals. The use of the axially fuel staged combustion method, in the form of reacting jet in reacting cross flow, for the next generations of gas turbines has attracted significant attention for raising turbine inlet temperature without increasing NOx emissions and providing a greater turn-down ratio. Jet-in-crossflow, which is a representative flow structure in axial staged combustion, has been studied for decades because of its unique flow structures and a wide variety of applications[7,8]. Many studies about reacting jet-in-crossflow in gas turbine applications have been conducted to investigate in perspective of hydrodynamics, stabilization, and emissions[9-11]. Despite the importance of understanding the dynamics of combustion system, the influence of axially staged multiple reaction zones on the development of self-excited combustion instabilities is not well understood. To address this issue, here we experimentally investigate the combustion dynamics in a staged combustion environment by a laboratory-scale gas turbine combustor equipped with two axially staged combustion regions.

2 Experimental methods

The laboratory-scale lean-premixed combustion test facility having two axially distributed combustion zone, depicted in Fig. 1, consists of four sections: a nozzle assembly section located upstream of the rig, a primary combustion zone, a secondary combustion zone, and a variable-length flame tube including a water-cooled exhaust. Two electric heaters are used to elevate the temperature of reactant mixtures, dry air and fuel, which are fully premixed before they enter the nozzle assembly section. The mass flowrates of air and fuel into the primary and secondary combustion chambers are controlled separately using thermal mass flow meters. The fully-premixed reactant mixtures are supplied equally via an annular perforated plate to each nozzle. Choked orifices are installed at each nozzle 333 mm upstream of the

Correspondence to: yongseok_choi@kaist.ac.kr

combustor dump plane to provide a well-defined acoustic boundary condition. The primary injector consists of sixty identical swirl nozzles, as described previous studies[12,13]. The secondary combustion chamber having a rectangular flow path is designed modular, providing jet injection locate variations, optical access, laser diagnostics, and pressure measurements. The downstream flame tube section provides adjusting the combustor length, defined as the distance between the combustor dump plane and the base of the piston head, by moving the water-cooled piston centered in the tube.

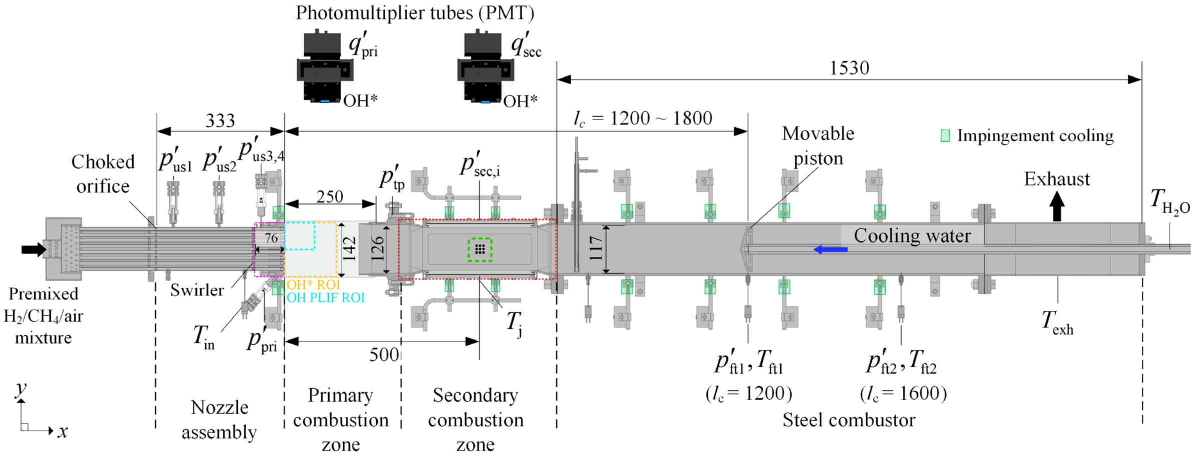

Figure 1: Cross-sectional view of an axial-fuel-staged lean-premixed combustor composed of four sections. p_i and T_i indicate dynamic pressure transducers and type-K thermocouples. Abbreviations: us = upstream, pri = primary, tp = transition piece, sec = secondary, ft = flame tube, exh = exhaust section. Dimensions in millimeters.

High frequency-response, water-cooled, piezoelectric pressure transducers(PCB, 112A22) were used to measure dynamic pressure in the inlet plenum and the combustor sections, as indicated in Fig. 1. To measure the temporal variations of the OH* chemiluminescence of each combustion chamber, photomultiplier tube(Hamamatsu, H7732-10) coupled with a bandpass interference filter (309 ± 5 nm) was used, located at 90° with respect to the flow direction. To capture unsteady flame dynamics, a high-speed CMOS camera(Phantom, VEO 1010L) and an ICCD camera(Princeton Instruments, PI-MAX4) was used respectively. The OH PLIF measurements are also conducted to each combustion zone by using Nd:Yag laser(Continuum, Surelite II-10) and tunable dye laser(NarrowScan, Radiant Dyes).

Table 1: Summary of all test conditions.

Test points	$P_{\mathrm{th,pri}}$ (kW)	$P_{\mathrm{th,sec}}$ (kW)	X_{H2}	ϕ_{pri}	ϕ_{sec}	ϕ_{g}	$T_{\mathrm{ad,pri}}$ (K)	u_{pri} (m/s)	u_{∞} (m/s)	u_j (m/s)	J
1	68	12	0.5	0.60	0.80	0.69	1834	27.8	16.6	15.6	5.3
2	64	16	0.5	0.60	0.80	0.71	1834	26.1	15.6	20.8	10.6
3	60	20	0.5	0.60	0.80	0.73	1834	24.5	14.6	26.0	18.9
4	56	24	0.5	0.60	0.80	0.74	1834	22.9	13.7	31.2	31.2

The total thermal input power is constantly maintained at 80 kW and separated into certain ratios to the primary and secondary combustion chambers. The fuel composition used in this study is even blends of

H_2/CH_4. The primary combustor operates at a fixed equivalence ratio of 0.6 and the secondary combustor's equivalence ratio is varied from 0.5 to 0.8. For a given set of inlet conditions, stationary measurements of self-excited instabilities were carried out by carefully adjusting the combustor length between 1200 and 1800 mm in 50mm increments. All test conditions are summarized at table1.Continue your text here.

3 Results and Discussion

We investigate the influence of introducing secondary combustion on the developement of self-induced pressure oscillations and interaction between reacting jet-in-crossflow and acoustic mode of the combustor system. To figure out the impact of the existence of secondary combustion on the combustor's overall stability, iso-contour stability maps are plotted based on four test conditions, whose secondary combustor's equivalence ratio changes from 0.5 to 0.8 by 0.1 increments, including 52 data points. Peak-to-peak pressure amplitude, measured at the primary combustor dump plane, is represented in Fig 2a, peak-to-peak heat release rate oscillation amplitudes from each combustion zone are plotted separately in Fig 2b and 2c, and Fig 2d represents the order of acoustically-coupled longitudinal eigenmodes which is calculated by FEM-based Helmholtz simulations(in COMSOL Multiphysics software package)[14].

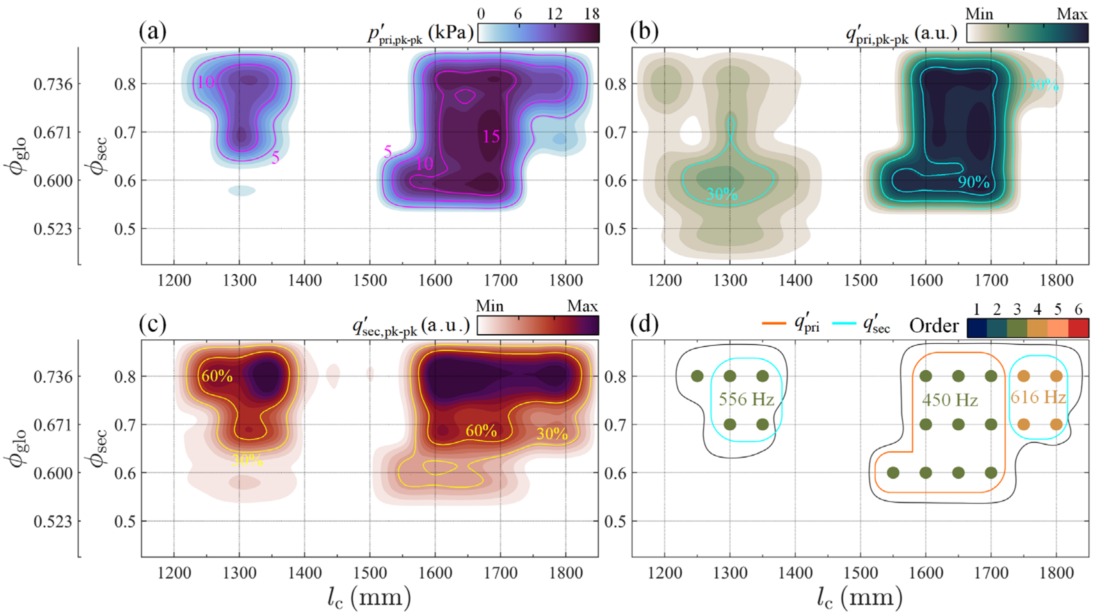

Figure 2: Stability maps plotted as a function of equivalence ratio of the secondary combustor and combustor length; cutoff amplitude for pressure perturbations is set to 1.0 kPa (peak-to-peak). (a) peak-to-peak pressure fluctuation amplitude. Magenta numbers indicate pressure amplitude of selected iso-contours (unit: kPa). (b, c)Peak-to-peak heat release rate ocsillation intensities from both combustion chamber. (d) Orders of longitudinal modes calculated from FEM-based Helmholtz simulations**.**

Fig. 2a shows that at the higher equivalence ratio(ϕ_{sec}) of jets injected secondary combustion zone, high-amplitude pressure fluctuations are generated at most combustor length conditions except 1400-1500 mm. According to the eigenmode calculation, two unstable regions corresponding to 1250-1350 mm and 1550-1800 mm are closely related to the L3 and L4. Surprisingly, heat release rate fluctuations of both combustors appear to be non-coincidence with each other and pressure fluctuations. We observe that the L3-coupled and L4-coupled instabilities develop without severe primary flame oscillations at

1350 mm and 1800 mm, respectively. In these cases, the heat release rate oscillations of reacting jet-in-crossflow in the secondary combustion zone emerge with large amplitudes and at these combustor length conditions, the formations of a pressure anti-node in the secondary combustion chamber were found by FEM simulation. These results suggest that the instabilities of the entire combustion system can be driven by a combination of the reacting jet-in-crossflow and the shape of the acoustic field. On the other hand, interestingly when the secondary combustion chamber operates in the lean equivalence ratio of 0.5, overall combustion instabilities are suppressed even operating condition of the primary combustor is unchanged. From the results, the stability of the combustion system can be varied dramatically by introducing axial-staged combustion in form of reacting jet-in-crossflow.

4 Conclusions

With the aim of understanding the influence of axially staged combustion on the dynamics of the entire combustion system, we experimentally investigated using a laboratory-scale gas turbine combustor equipped with two axially staged combustion regions. Under the constant thermal input power, we changed jet equivalence ratio of the secondary combustion zone from 0.5 to 0.8. When the jets are injected with rich conditions and located at the pressure anti-node of the combustor, jet flames of the secondary combustion zone oscillate vigorously without primary flames' fluctuations. This means that the combustion system with axial-staged combustion can be unstable not only by the primary flames but also by the secondary flames. By contrast, overall instabilities are suppressed when the jet is injected in a lean condition. These are crucial findings of axial-staged combustion suggesting that instabilities induced by the secondary combustion zone have to be considered when designing the axial-staged combustor and the equivalence ratios and locations of reacting jet-in-crossflow of the secondary combustion zone are the main factors of controlling the instabilities.

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