Numerical Investigation of Fuel Feed Line Instabilities and its Effects in the Partially Premixed Swirling Flame

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1 Introduction

Combustion instability in gas turbine combustors has been studied intensely because of its complexity and risk. The coupling of swirl flame with acoustics often leads to the generation of combustion instability in a combustor and should be prevented when operating the combustion system. Self-excited combustion instabilities are experimentally and numerically reproduced in laboratory scale combustors. From those studies, various factors including processing vortex core (PVC) [1], vortex shedding [2], and fuel composition [3] are reported to be the main cause of combustion instability. Still, relatively few works are reported on the role of the fuel feed line in the development of combustion instability. The complex structure of fuel feed line and swirler could possibly generate external non-uniformity and fluctuation of flow entering the combustor. In addition, the fuel-air mixing near the injector becomes an important issue. Franzelli et al. [4] pointed out that incomplete mixing in the combustor causes fluctuations of equivalence ratio and generates unstableness in the combustor. Durox et al. [5] investigated the impact of swirl number in the generation of PVC in the combustor. It is also found out that the change of blade angle at the swirler instigates fluctuations of heat release rate, which results in self-sustaining thermo-acoustic instability.

Based on the previous studies, the present work focuses on the fuel feed line in the partially premixed model gas turbine combustor and attempts to find factors triggering combustion instabilities through numerical simulation. The forced flame response approach is applied to exclude acoustics inside the combustor. Large eddy simulations (LES) are performed at various forcing frequencies, and transfer functions of velocity in fuel feed line are obtained. Simulations of the flame transfer function (FTF) and cold-flow transfer function (CTF) are subsequently performed to find out the flame response inside the combustor, which are described below.

$$FTF = \frac{(q'/\bar{q})_{flame}}{(u'/\bar{u})_{inlet}} \tag{1}$$

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$$CTF = \frac{(u'/\bar{u})_{swirler}}{(u'/\bar{u})_{inlet}} \tag{2}$$

Comparisons with experimental results are conducted, and the factors that contribute to instabilities are discussed.

2 Experimental and numerical set up

The partially premixed model gas turbine combustor shown in Fig. 1 was selected for this LES study.

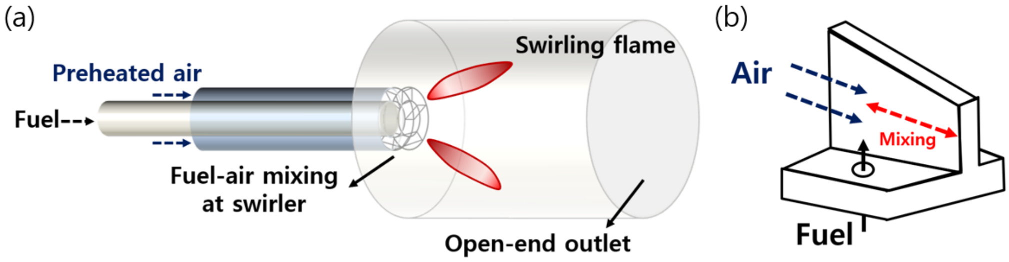

Figure 1: (a) Schematic of the partially premixed model gas turbine combustor and (b) fuel-air mixing in the swirler vane

Experiments under two different operating conditions were performed with/without the blocking nozzle at the combustor outlet [6]. Thermo-acoustic instability was excited and sustained with the nozzle at the exit, and the effect of fuel inlet condition on unstableness was reported. FTF/CTF were achieved with the acoustically forced fuel, and a noticeable peak in gain was shown at the low-frequency domain. Three parts namely the fuel feed line, swirler, and combustor constitute the experimental setup, which is described in Fig. 1a. The fuel feed line at the left side supplies the preheated air and fuel into the combustor. The mechanical pulsator (siren) is located at the inlet of the fuel feed line to provide the acoustic forcing. The forcing frequency was set from 50 to 600 Hz, and the forcing magnitude was set under $|u'/\bar{u}| = 0.1$. Air was uniformly supplied at a temperature of 473 K and mass flow rate of 0.0236 kg/s. The fuel was supplied at room temperature with a heating value of 40 kW. The mixing of fuel and air occurred at the short mixing zone inside a swirler. The swirler was composed of 14 swirl channels (swirl number: 0.832), and the detail of the mixing process in a single channel is described in Fig. 1b. The fuel was injected in the form of a jet in the crossflow and mixed with the supply air. The fuel-air mixture was not perfectly premixed in the swirler due to the short mixing length of 2.7 mm. In the combustor, a V-shaped swirling flame was generated. The combustor outlet was exposed to ambient air for FTF/CTF measurements (Fig 1a), and therefore, combustor acoustics were neglected.

Simulations were performed for the experimental domain in Fig. 1. The flow equations consisting of the Favre-filtered mass, momentum, energy, and species were solved for the resulting turbulent reacting flow problem. LES WALE model [7] was used for closing the governing equations and PaSR (Partially Stirred Reactor) model was applied to model the turbulence-chemistry interaction. A multi-step chemical scheme [8] was used to predict the partially premixed flame in the combustor. Unstructured mesh was used in the computational domain, while structured mesh was used in the boundary layer at the wall with $y^+ < 5$. The mesh was refined near the mixing layer and the reaction zone, and contained 3.6 million hexahedral cells.

Dirichlet boundary conditions of velocity, temperature, and species were applied at the inlet of the fuel feed line. The details of the fuel supplement in the acoustically forced condition are shown in Table 1.

Table 1: Input values of the simulation.

Inlet conditions	Value
Mean velocity	11.02 m/s
Forcing magnitude	1.102 m/s
Forcing frequency	50 – 400 Hz
Temperature	320 K
Composition	H2/CH4 : 50/50
Wall condition	Isothermal

In the uniform inlet condition, the fuel was supplied with a velocity of 11.02 m/s without additional forcing. The air was supplied with the velocity of 41.85 m/s and at a temperature of 473 K. Isothermal wall was applied as the wall boundary condition and pressure outflow condition was applied at the combustor.

4 Result

The simulation without the acoustic forcing was performed to capture the naturally occurring instability inside the fuel feed system.

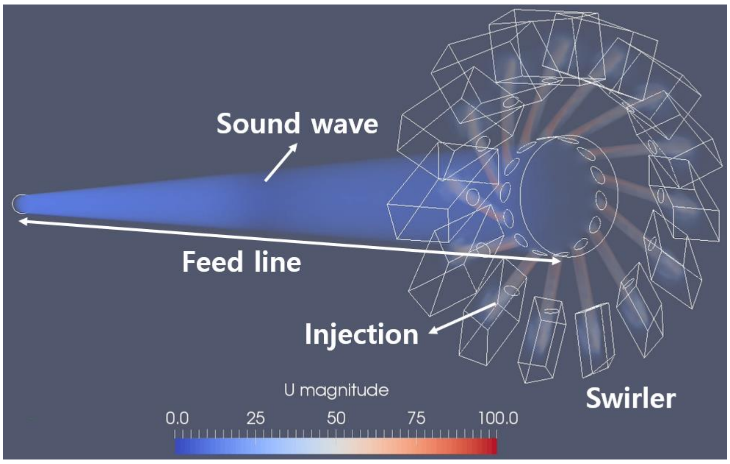

Figure 2: Instantaneous snapshot of the velocity in the fuel feed system

An instantaneous snapshot of the calculated velocity field in Fig. 2 shows the flow structures in the fuel feed system. The velocity is supplied at the inlet boundary that induces the acoustic wave inside the fuel feed line. At the right end of the fuel feed line, 14 injectors connect the feedline to swirl channels. The supplied flow is injected through the swirler that mixes with air at each swirl channel. Turbulence develops near the boundary layer due to high Reynolds number of the channel flow (Re = 8700). Sharp edges at the ends of the injectors generate extra vortices, which produces kinetic energy at the corresponding region.

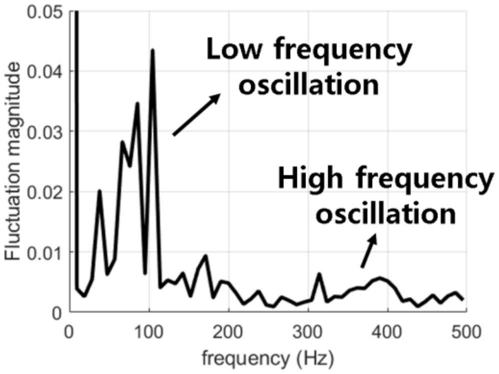

Figure 3: FFT result of the flow velocity at the swirler outlet

A fast Fourier transform (FFT) result in Fig. 3 shows the frequency spectra of the unstable flow in the swirler outlet. Low-frequency oscillations around 50-100 Hz and high-frequency oscillations around 300-400 Hz are observed. Interactions between the feed line turbulence and vortices near the injectors induce the instability, which causes low-frequency oscillations inside the swirler. The longitudinal acoustic mode of the feed line induces high-frequency oscillation, but the magnitude of this oscillation is relatively low. The naturally occurring oscillation resonate with the acoustically forced velocity, which results in high gain of CTF and FTF.

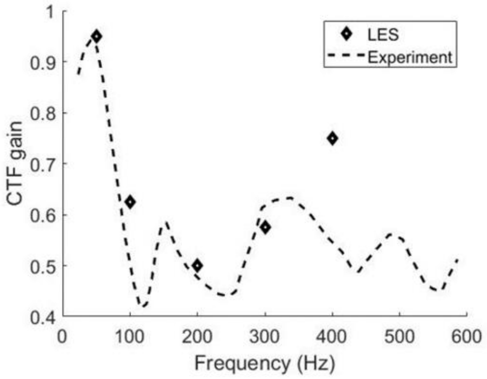

Figure 4: LES (doted) and experimental (line) results [9] for CTF gain

A good agreement with the experimental data [9] is shown in Fig. 4. Noticeable peaks are observed at the frequency of 50 and 400 Hz, which coincide with naturally occurring oscillation frequencies in Fig. 3. The discrepancy at 400 Hz with the experiment is presumed to be an over prediction of the strength in the acoustic wave. The presented CTF peaks are similar to the reported FTF results [6], while a single numerical simulation with the forcing frequency of 50 Hz is performed in the present work. The FTF gain from the numerical simulation is around $|FTF|=3$, which is similar to the experimental result [6].

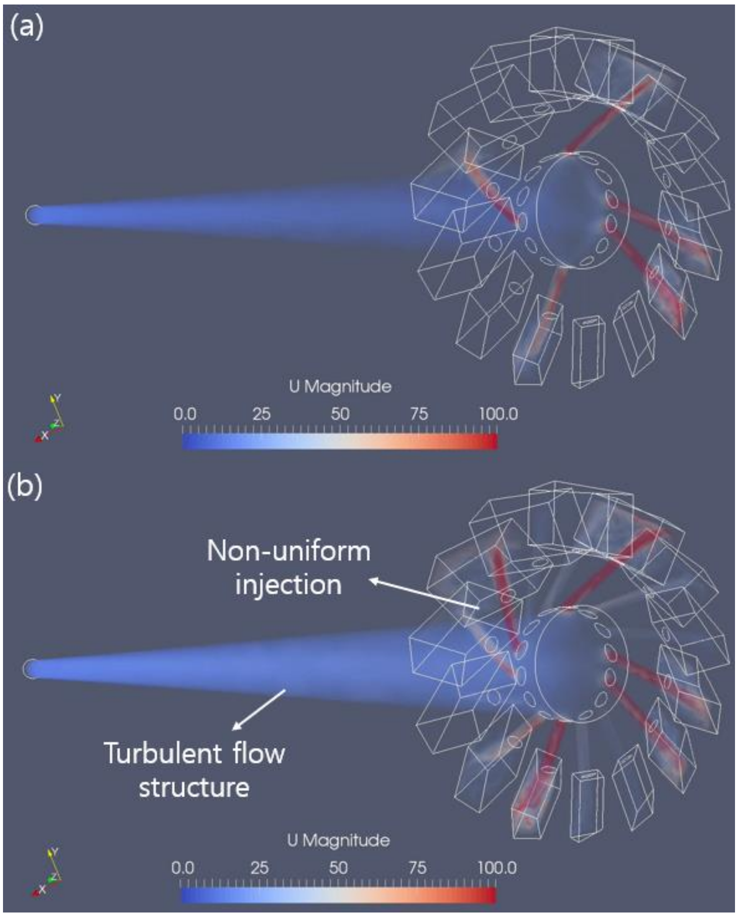

Figure 4: LES results for acoustically forced flow at 50 Hz, where the mass flow rate to outlet is (a) the lowest and (b) the highest

Figure 4 presents the acoustically forced flow structures in the fuel feed line and swirler. The development of turbulent boundary layer is observed through the feed line wall, and it induces non-uniform injection through the swirl channel. The flow injection is mainly shown at around 5 injectors (Fig. 4a), while the intermittent injection is shown at other injectors (Fig. 4a and Fig. 4b). These periodic injections cause the fluctuation of supply fuel in the combustor.

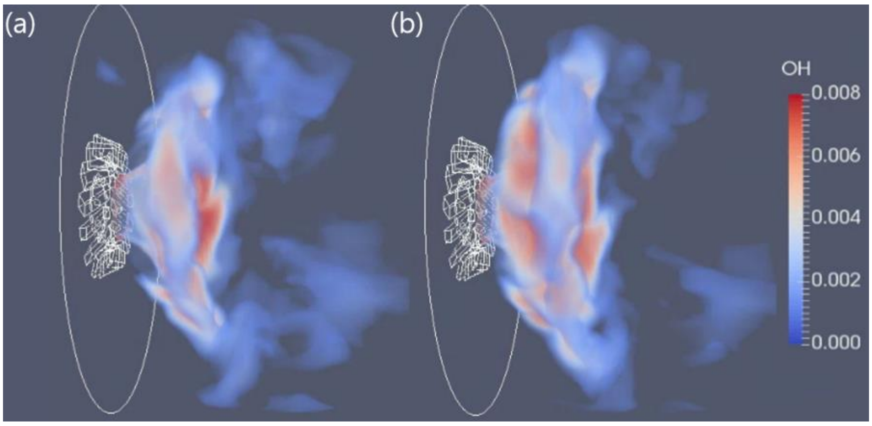

Figure 5: LES results for acoustically forced flame with 50 Hz with (a) the lowest and (b) the highest mass flow rate into the combustor

The fluctuation of the forced swirling flame is described in Fig. 5. An attached flame is generated inside the combustor, and it fluctuates in the radial direction due to the supply flow oscillation. Additional oscillation is not shown due to the non-reflective boundary condition at the combustor outlet. Reactions are mainly progressing near the dump plane of the combustor, and burnt gases recirculate through the radial direction. The interaction of flame with the recirculation zone at the combustor wall causes heat release oscillations, which results in peak FTF gain in the low-frequency domain.

5 Conclusion

LES work on the partially premixed model gas turbine combustor is performed. Good agreements are confirmed with the experimental data, showing that LES can reliably describe the transient flow physics in the fuel feed line and the combustor. The simulation results show that a turbulent boundary layer is developed through the fuel feed line. The developed turbulence further interacts with vortices near the injector, producing high kinetic energy. FFT result of the outlet velocity shows that the frequency of naturally occurring instability is around 50-100 Hz. The developed instability resonates with the forcing velocity, which results in peak CTF gain in the low-frequency region. The FTF results from the combustor show that the swirling flame fluctuates in the radial direction and produces heat release oscillations. Therefore, peak gain at the low-frequency domain is observed in the FTF result.

This study suggests fundamental causes of instability inside the fuel feed line and discusses about FTF/CTF characteristics in the combustor. The present findings can be utilized in the effort to suppress the thermo-acoustic instability inside the combustion systems.

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