Influences of Fuel Supply-Driven Instability on Flame Transfer Functions and Combustion Instability

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1 Introduction

Most industrial gas turbine engines are prone to unexpected oscillations inside the combustion chamber. Among them, thermoacoustic combustion instabilities are hard to predict and cause safety issues in gas turbine engines. Pressure fluctuations due to instabilities could provoke and trigger major combustion problems like vibration, flame flashback, structural damage, and the explosion of engines [1]. The criterion for combustor stability is mathematically defined as the Rayleigh criterion (Eq. 1), and has been studied over the decades to identify the causes of combustion instabilities in gas turbine engines:

$$\oint p'Q'dt > 0 \tag{1}$$

In the above equation, p' is pressure fluctuation and Q' is heat release rate fluctuation at the flame. In previous studies, flow-induced instabilities like precessing vortex core [2] inside the combustor were experimentally investigated as the driving mechanism of combustion instabilities. Those flow instabilities directly influence the ignition and burning of the flames, which result in heat release fluctuation. Combustor and feedline structures are also considered to be crucial factors which can elevate the effect of combustion instabilities. The high Reynolds number in the fuel supply system leads to complex flow patterns and potential instabilities, which can result in fuel starvation, uneven fuel distribution, and reduced combustion efficiency. To address these challenges, the design of the fuel supply system must consider fluid mechanics principles, and incorporate features such as properly sized and located injectors, proper flow shaping, and proper fuel pressure regulation. However, flow-induced instabilities inside the feedline part have not been intensely studied as a cause of combustion instability since the experimental measurement is rarely performed inside the fuel supply part. Therefore, the present study focuses on the fuel supply-driven instabilities in the model gas turbine combustor and investigates the factors which potentially trigger combustion instabilities.

High-fidelity numerical simulations are carried out to complement the absence of flow details inside the fuel supply system. Both flame transfer function (FTF) and self-excited combustion instability are numerically captured inside the combustor, and oscillation characteristics inside the fuel supply system are figured out. Comparison with the existing experimental results is conducted to verify the numerical results, and the influencing factors contributing to FTF and combustion instability are discussed.

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2 Target configuration

Figure 1 describes the partially premixed model gas turbine combustor, which is investigated in the current numerical study.

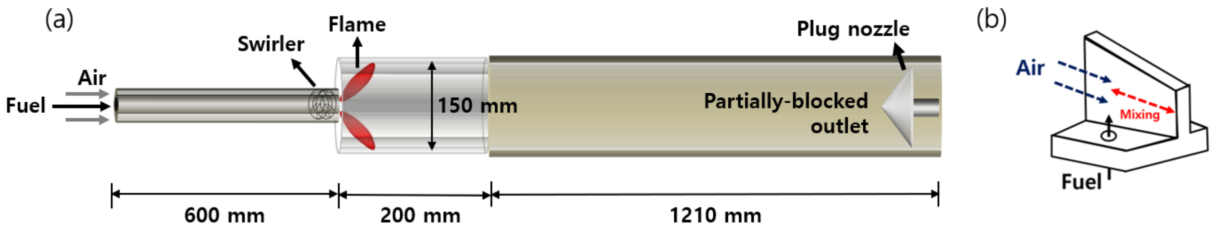

Figure 1: (a) Schematic of the partially premixed model gas turbine combustor and (b) the swirler vane

Previously, an experiment [3] was conducted to identify the unstable flame and combustion instabilities inside the cylindrical combustor. The fuel and air are injected separately through the feedline for the experiment. The supplied fuel and air are partially mixed inside a swirler at the short mixing length of 3 mm (Fig. 1b). Inside the combustor, a V-shaped swirling flame is formed due to a torch ignitor located at the combustor upstream. Right-end of the combustor is partially blocked with the plug nozzle, generating an acoustic effect inside the combustor. Experimental measurements of flow using the particle image velocimetry method, and flame using the OH-chemiluminescence method were performed inside the 200 mm long transparent quartz tube, located from the combustor entrance. Combustor pressure is measured using the dynamic pressure sensors located through the combustor wall. Hydrogen-enriched methane gas with a 50:50 molar composition ratio is selected as the fuel. The mass flow rate of the fuel is set as 102 slpm (standard liter/min) with a temperature of 320 K, an equivalence ratio of 0.56, and a heat input of 40 kW. Also, the airflow rate is set as 1100 slpm with a temperature of 473 K. Meanwhile, in the FTF experiments, the plug nozzle is not used in the combustor, and therefore, combustor acoustics is not considered. Flow speed and temperature are set the same as injecting gases, while the mechanical pulsator (siren) gives the acoustic forcing of the supplying fuel flow. The forcing magnitude is set under $|u'/\bar{u}| = 0.1$ and the forcing frequency is set from 50 to 600 Hz, where u indicates flow speed.

In this work, the open-source CFD framework OpenFOAM is used for the high-fidelity numerical simulation of the gas turbine combustor. In the solver, the Favre-filtered flow equations of mass, momentum, energy, and species are implemented. The PIMPLE algorithm is applied to properly handle pressure-velocity coupling in the governing equations. Inflow gases are assumed to an ideal gas, and enthalpy and specific heat of species are calculated using on NASA polynomial equations. The molecular diffusivity of gas is modeled using the Chapman-Enskog theory considering Nitrogen as the carrier gas to handle non-unity Lewis number of hydrogen-enriched gas. Also, the flow viscosity is calculated depending on the flow temperature using Sutherland's viscosity law. The subgrid-scale viscosity term in the governing equation is calculated using WALE model [4], and therefore, small-scale eddies are assumed using the LES model. For the combustion modeling, the reduced reaction mechanism consist of 23 reactions and 15 species [5] is used to solve the reaction rates of the hydrogen-enriched methane fuel. To resolve the subgrid scale reactions inside the combustor, partially-stirred reactor (PaSR) model is additionally considered in the reaction model.

In the simulation, the non-slip adiabatic wall boundary condition is applied through the rigid wall. Non-reflective outlet condition is used at the open-end combustor outlet. Unstructured grid is used to handle complex geometries of feedline and swirler. The grid is locally refined at the flame generation area and near the edges. Total of 5.86 million cells are used for the simulation of FTF, and 7 million cells are used for the simulation of combustion instability.

3 Result

The flame transfer function (FTF) and the cold-flow transfer function (CTF), which are mathematically defined below equations, are used to quantitatively define the flame and flow responses in the combustor.

$$FTF = \frac{(q'/\bar{q})_{flame}}{(u'/\bar{u})_{inlet}}, \; CTF = \frac{(u'/\bar{u})_{outlet}}{(u'/\bar{u})_{inlet}}$$

In the above equations, u indicates flow speed and q indicates heat release rate in the gas turbine engine. Previously, CTF is used to investigate the fuel injection patterns in the rocket propulsion system and flow responses in the gas turbine combustor. CTF function is measured at six different forcing frequencies and a comparison with the experimental result is shown (Fig. 2).

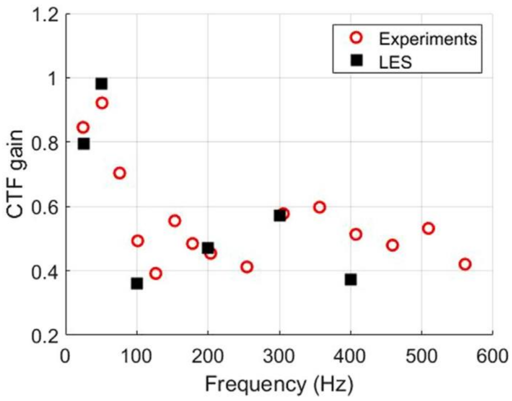

Figure 2: The experimental and numerical results for the CTF gain function

The simulation results of CTF function predict the experimental results correctly in various forcing frequencies. CTF gain is calculated below 1, indicating that the inlet fluctuation is dissipated inside the fuel feedline. Local maxima of CTF gain are shown at the forcing frequencies of 50 and 300 Hz same as the experimental results.

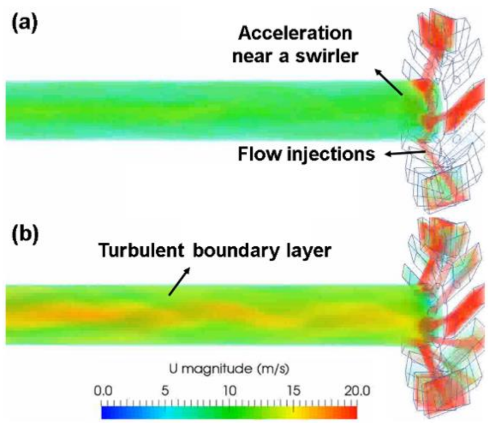

Figure 3: Velocity distribution inside the fuel supply system with (a) minimum and (b) maximum mass flow rates to a swirler at the forcing frequency of 50 Hz

Unsteady flow inside the fuel supply system is described at two different phases of minimum and maximum mass flow rate to a swirler in Fig. 3. Turbulent boundary layer is developed through the feedline due to the high Reynolds number of 5630, and it results in the non-uniform flow distribution inside a swirler. Also, in the simulation, periodic fuel injection through a swirler appeared and it results in a high gain of CTF function inside a swirler. To further investigate the cause of flow responses and internal instabilities, simulation without any external forcing is carried out. The oblique view of the fuel supply system (Fig. 4a) shows the instantaneous flow distribution.

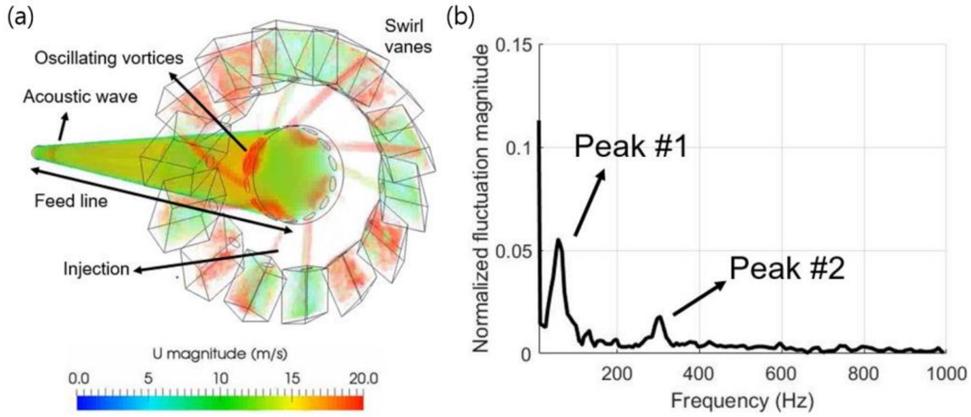

Figure 4: (a) Oblique view of the flow velocity inside the fuel supply system and (b) FFT spectrum of the flow rate at the swirler outlet

As shown in Fig. 4a, periodic injection into a swirler is observed without external forcing at the frequency of 50 Hz, implying that the periodic injection is self-induced in the fuel supply system. The acoustic wave at the frequency of 300 Hz is preserved inside the fuel supply system since the rigid wall blocks the right end of the fuel feedline. Based on the internal flow instabilities, the fast Fourier transform (FFT) result of internal oscillations is drawn in Fig. 4b. In the FFT result, two dominating oscillation frequencies are shown due to the periodic injection (peak #1) and the feedline acoustics (peak #2). Relatively weak oscillations are also shown due to the turbulences inside the feedline and swirler. Oscillation inside the fuel supply system influences the dynamic flame responses in the combustor as shown in the FTF profiles in Fig. 5.

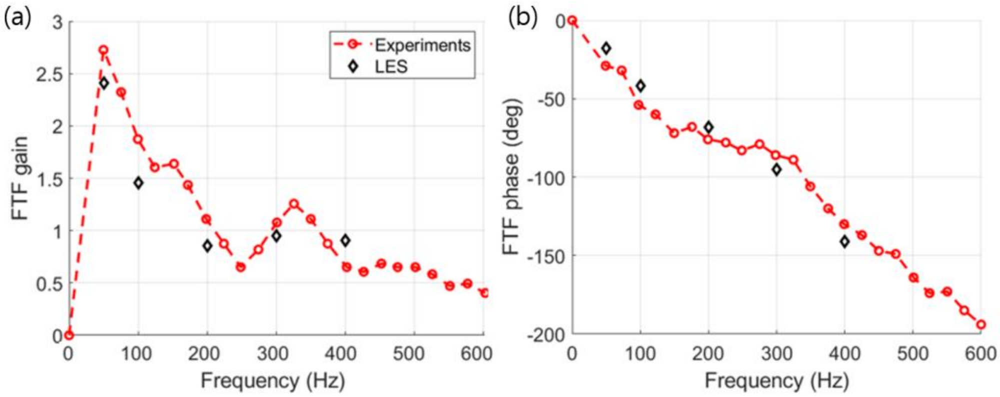

Figure 5: (a) FTF gain and (b) FTF phase calculated from the simulations

The FTF profiles in the Fig. 5 are calculated by integrating the heat release rate inside the combustor. In the simulations, the flame responses and time lags are similar to experimental results, which shows the reliability of current numerical works. Both FTF and CTF (Fig. 2) indicate the maximum gain at 50 Hz due to the coupling of periodic flow injection and inlet velocity fluctuation. Therefore, the self-induced instabilities in the fuel supply system result in unexpected peaks in flow and flame response, affecting combustion instabilities inside the combustor.

The impact of fuel injection on triggering the combustion instabilities is further investigated by capturing combustion instabilities in various mixing conditions. Simulations are performed in partially premixed and premixed conditions, and the frequency spectra of the dynamic pressures inside the combustor are shown in Fig. 6.

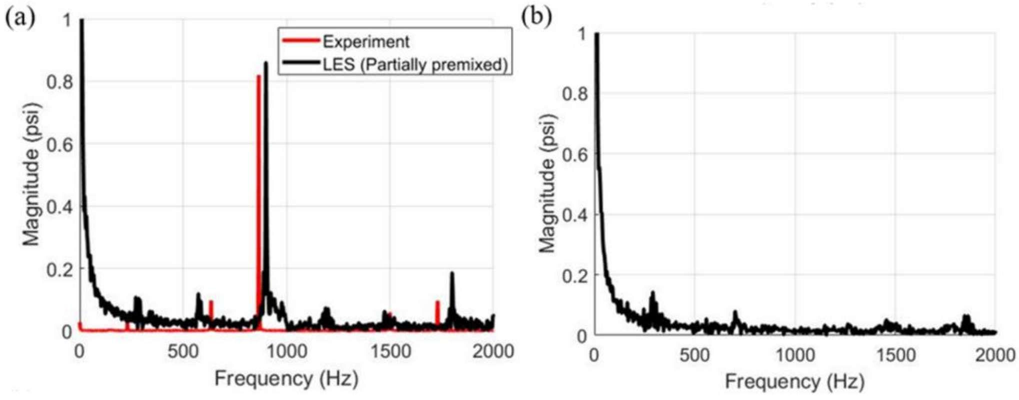

Figure 6: Pressure spectrum inside the (a) partially premixed and (b) premixed combustor

The pressure is measured at 1.02 m from the combustor dump plane for 0.1 seconds. In partially premixed condition, the peak frequency is shown near 900 Hz in both the experiment and simulation. Oscillations in the frequencies of 300 Hz and 600 Hz are weakly shown, which correspond with the natural frequency and 2nd harmonics of the combustor, respectively. In the perfectly premixed flame, on the other hand, the relatively weak oscillation was shown at the frequencies of 300 and 700 Hz. That weak oscillation shows that the combustion instability feedback loop did not appear in the premixed case.

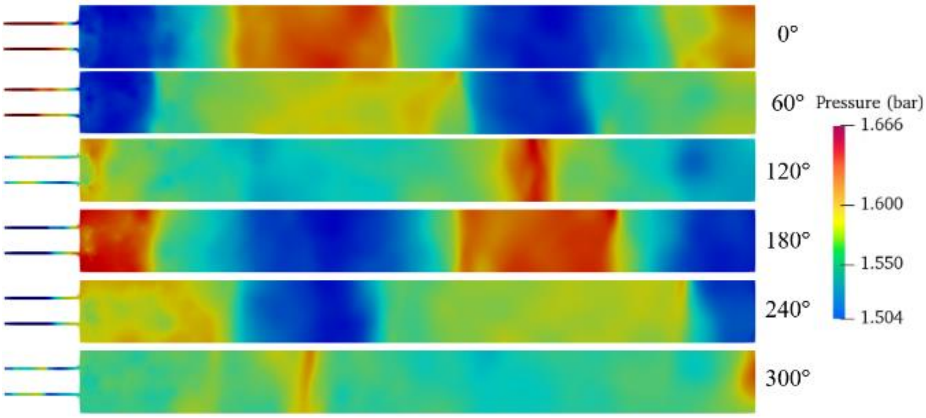

Figure 7: Pressure fields inside the partially premixed gas turbine combustor with six different phases

The phase-locked dynamic pressure fields in a single combustion instability oscillation cycle are shown in Fig. 7. The pressure oscillation appears from the feedline to the combustor and it indicates that the oscillation inside the feedline is included in the combustion instability feedback loop. The local changes of pressure are shown near the combustor entrance due to the formation of flame.

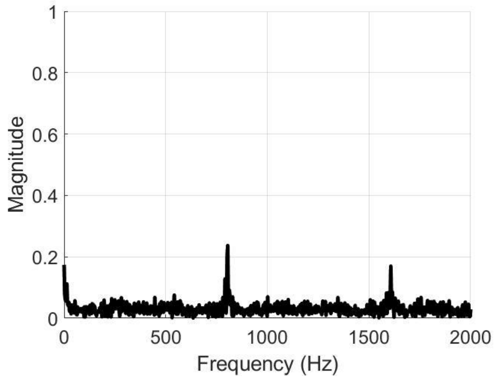

Figure 8: Pressure fields inside the partially premixed gas turbine combustor with six different phases

Figure 8 shows the frequency spectra of the equivalence ratio inside a swirler. The peak frequency near 900 Hz was shown, which was the same peak frequency with combustion instability. Therefore, the pressure wave at 900 Hz (3rd harmonics) induced the oscillation of flow in the supply line, and it caused instability during the mixing process. Since the equivalence ratio was fixed at all regimes, the oscillation during fuel-air mixing did not appear in the perfectly premixed case. Therefore, the oscillation of the equivalence ratio before ignition indicates that imperfect mixing with fuel and air affected the combustion instability in the partially premixed combustor.

4 Conclusions

The fuel supply system-driven instabilities on partially premixed combustors are investigated using high-fidelity numerical simulations. The self-induced vortices in the fuel supply system impeded the fuel supply into the swirler and caused the periodic fuel injection at 50 Hz, which results in a strong flow response in the combustor. Such oscillatory fuel supply resulted in a rigorous fluctuation of flames and the subsequent increase of the FTF gain. Furthermore, combustion instability is simulated in the combustor and the unstable result is found in the partially premixed condition. In partially premixed combustion, the FFT spectra of the equivalence ratio inside a swirler show a similar distribution with the frequencies of combustion instability in the combustor. Therefore, it implies that the mixing process of fuel and air contributes to the feedback mechanism of combustion instability in partially premixed conditions.

References

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