Numerical studies of hydrogen-enriched partially premixed combustion on a model gas turbine combustor

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1 Introduction

The most commonly used method for the operation of gas turbines is combustion of natural gas, which is composed of several hydrocarbon mixtures. However, there is a problem that hydrocarbon fuels generate large amounts of nitrogen oxides and carbon monoxide. In order to reduce this, burning at low temperature is used in a lean condition. Still, under such conditions, flame may be turned off due to instability such as blowout, flashback, and the operation may stop. Therefore, a method of using synthetic gas has been attracting attention as a way to overcome these existing problems. Among them, hydrogen content in syngas greatly changes the combustion characteristics such as exhaust gas emission and flame generation. Experimental studies have been reported in the past regarding this. Kim et al. [1] confirmed that high combustibility of hydrogen fuel greatly improves the flame stability and changes the reaction zone. Cozzi et al. [2] investigated gas emissions and flame stability by hydrogen content and confirmed that an increase in hydrogen composition produced a more stable flame. Previous studies [3,4] also indicate that a change in the content of hydrogen in syngas modifies the tendency of thermo-acoustic instability occuring in a combustor. However, numerical approach to properly simulate the hydrogen-enriched effect is currently uncommon, and additional research is needed [5].

In this study, simulations are carried out on a hydrogen-enriched partially premixed model gas turbine combustor. Synthetic gas consisted of methane and hydrogen is considered as working fuel, and the influence of hydrogen composition in the reactive flow is investigated. For accurate simulation of swirl-stabilized flame inside the combustor, large eddy simulation (LES) is applied within the OpenFOAM framework. Comparisons are made with experimental PIV and OH-Chemiluminescence data for verification of simulation. Changes in hydrogen composition also affects the combustion instability, and such related findings are also reported herein.

2 Numerical setup

A 1/3-scale GE7EA model gas turbine combustor was selected as a target for numerical simulation, and its schematic diagram is shown in Fig. 1. The combustor had a length of about 1.41m in the axial direction and a swirl nozzle was located at the inlet of the combustor. The combustor outlet was blocked with a water-cooled plug nozzle to achieve an acoustic boundary at the outlet. For combustion, air was fed into the swirl nozzle at 200 ° C and fuel was injected from 14 holes located in the nozzle. After that, fuel and air were allowed to enter into the combustor after being partially premixed in 2.7 mm long mixing zone inside the nozzle. The particle image velocimetry (PIV) technique was applied to measure the velocity field in the combustor, and OH-chemiluminescence measurement was performed to measure the flame structure. The pressure inside the combustor was obtained with 11 dynamic pressure sensors located on the wall.

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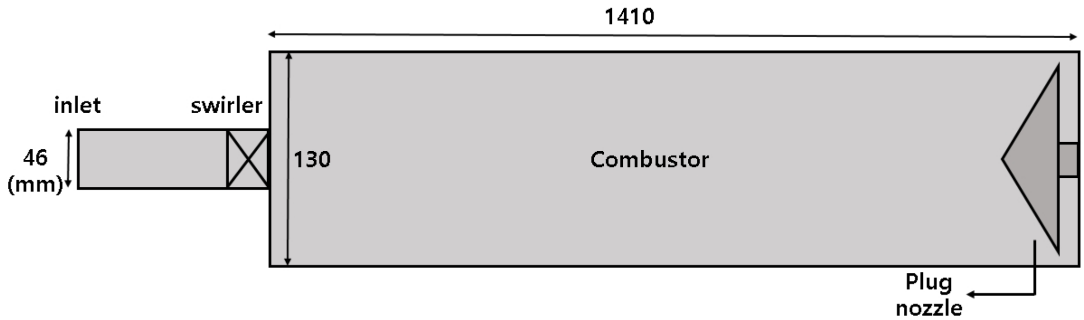

Figure 1. Schematic of model gas turbine combustor

For accurate modeling of such combustor, production of STL files using open-source software SALOME was preceded. The generated STL file was applied to a CFD package OpenFOAM, and the computation was progressed. The generation of unstructured grid used in this analysis was carried out using cfMesh, a volumetric mesh generation program, and the size of the grid was set differently in each analysis section for efficient calculations. First, a grid size of about 2 mm was selected in the injector to effectively resolve the turbulent flow in a narrow section. In the swirler nozzle where fuel and air are partially premixed, a very fine unstructured grid of about 0.3 mm length was applied to accurately simulate the mixing process. The mixed fuel and air were injected into the combustor with a swirl number of about 0.832. In the combustion section, a fine grid of about 2 mm length was used, and a coarse grid of about 4 mm length was used in the non-combustion section. The grid distribution and shape of the swirl nozzle are shown in Fig.2.

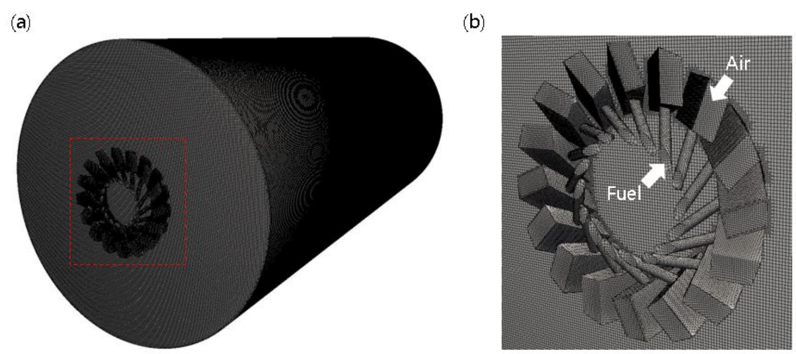

Figure 2. (a) Grid distribution (horizontal cut at the entrance of the swirl nozzle) in the computational domain and (b) injection locations of the fuel and air

LES was applied to calculate the high-speed swirl flow in the combustion chamber and subgrid-scale modeling was performed using the WALE model. In addition, the PaSR model was applied to precisely simulate sub-grid scale chemical reactions in the combustion chamber. In order to investigate the hydrogen enrichment effect in the combustion chamber, following four fuel compositions were considered (Table 1).

Table 1: Initial conditions of the simulated cases

Cases considered	A	B	C	D
H_2 ratio (mole fraction)	25	50	75	100
Equivalence ratio	0.565	0.552	0.529	0.480
Fuel flow rate (liter/min)	80.30	102.00	139.78	222.00
Air flow rate (liter/min)	1100	1100	1100	1100
Heat input (kW)	40	40	40	40

The initial conditions shown in Table 1. were applied to the inlet of the injector. Air is uniformly injected at a uniform speed of 1100 slpm(liter/min) with a temperature of about 470K. Injection speeds of fuel are varied depending on fuel conditions, while their temperatures are fixed at 320K. At all walls, no-slip adiabatic wall condition is applied.

3 Results

To verify the suitability of simulation, flame and flow field in the combustor were compared with the experimental OH-chemiluminescence results. First, comparisons of time-averaged flame images were conducted for three composition cases. Fig. 3 shows that numerical results of flame structures is able to predict results similar to experiments for various hydrogen compositions.

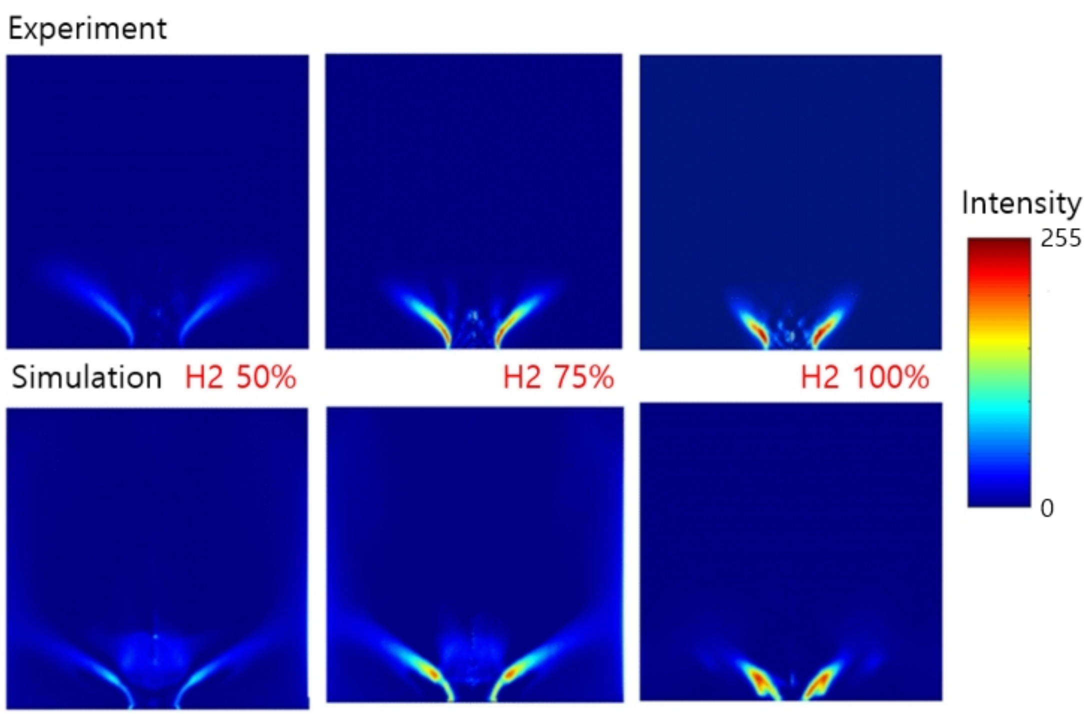

Figure 3. Experimental [6] and numerical flame results for various conditions

As the content of hydrogen in syngas increased, it was confirmed that the flame reacted rapidly in a narrow section due to faster flame speed and higher reactivity of hydrogen. The calculated velocity fields were also compared with the experimental PIV results, and good agreements are obtained under various conditions as shown in Fig. 4.

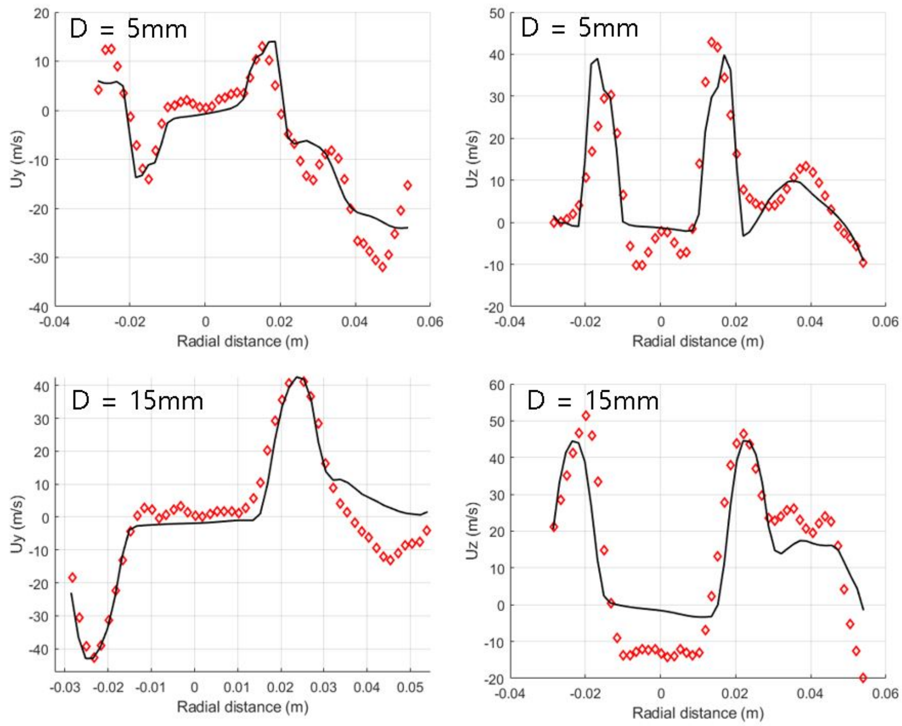

Figure 4. Profiles of time-averaged Uy, Uz velocity components in the combustor for experiments [6] (symbols) and simulations (lines) where D is the distance from the swirler nozzle

Furthermore, combustion instability characteristics excited inside the combustor were investigated. Calculations of combustion instability were carried out for about 0.3 seconds and the effect of hydrogen content was investigated. As a result of this calculation, it was confirmed that the combustion instability result similar to that of experiments was obtained as shown in Fig. 5.

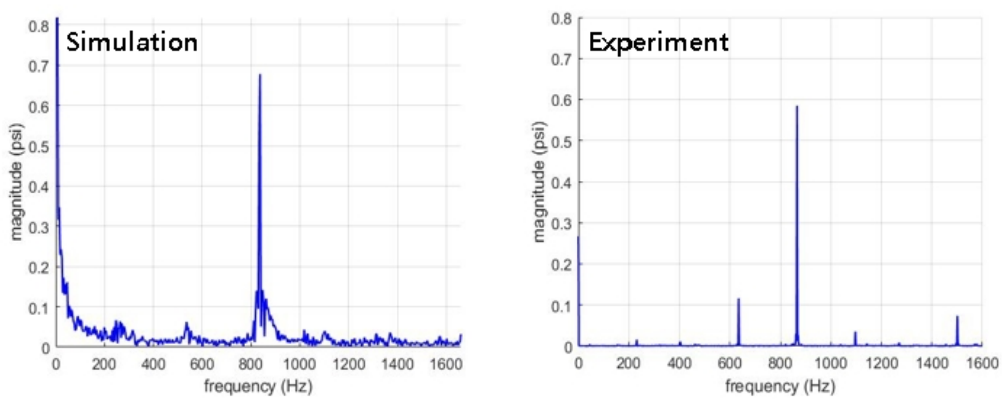

Figure 5. Numerical and experimental [6] FFT results for combustion instability analysis for Case B

According to the above result, the region of dominant combustion instability frequency is formed at 800 Hz, which corresponds to third axial mode of the combustor. Similar results were obtained for 25% and 75% hydrogen compositions.

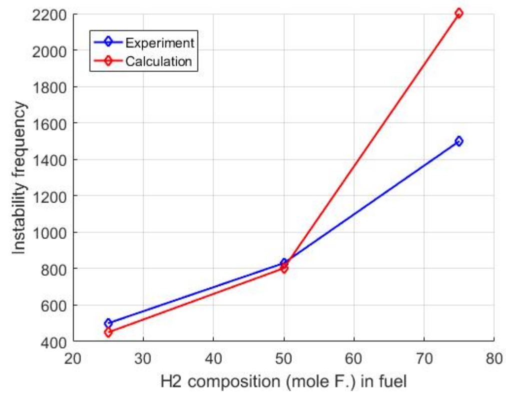

Figure 6. Instability frequency transition due to hydrogen composition

Fig. 6 shows the most dominant instability frequency for each hydrogen composition. As the content of hydrogen in the fuel increases, the frequency of instability in the combustor shifts to a higher frequency region. This tendency is consistent with results reported in experiments [3, 4], and is attributed to high flame speed of hydrogen. According to simulation results, the frequency range of combustion instability that occurred at 25% and 50% of H2 was predicted to be similar to experimental results. On the other hand, the frequency of combustion instability occurred under the condition of 75% H2 was different from experiments, and is assumed to be a consequence of an error in the calculation of the flame speed or the input flow rate. Subsequently, the calculation carried out under condition of 100% H2 resulted in almost no combustion instability. This result is in good agreement with experimental results, and is attributed to the fact that the generated flame structure is too short to interact with the rigid wall and recirculation zones.

4 Conclusion

Numerical investigations were performed on combustion characteristics in a hydrogen-enriched partially premixed combustor, which considered five different cases of varying hydrogen contents. The results showed that the flame structure changes significantly as the hydrogen content is varied. Then, the effect of hydrogen content on the thermoacoustic instability inside the combustor was investigated.

References

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