Combustion Oscillation Characteristics of Hydrogen-Rich Fuel

Akane Uemichi, Ippei Kanetsuki and Shigehiko Kaneko

Abstract In this study, combustion oscillation characteristics of hydrogen-rich fuel were investigated. The experimental results fueled by mixture of natural gas and hydrogen show that hydrogen-rich combustion influences on the oscillating frequencies. In the case of only natural gas, the single oscillating frequency around 350 Hz is obtained, and in the hydrogen-containing fuel case, the double oscillating frequencies around 200 and 400 Hz are measured. However, the latter oscillating frequencies could not be derived from the one-dimensional acoustic analysis. Therefore, to figure out these frequencies, the acoustic impedance was measured experimentally and the oscillating frequencies were re-calculated using the measured acoustic impedance as the acoustic boundary conditions. As a result, the 200, 350, and 400 Hz frequencies could be expressed using the acoustic impedances.

Keywords Combustion oscillation · Pressure oscillation · Hydrogen-rich fuel

1 Introduction

Combustion instability in a combustion chamber of a gas turbine has been one of the big problems because the resonance with various parts of a gas turbine leads to weariness or damages when combustion instability occurs [1]. Additionally, it is expected that using unused energy resources such as digestion gas, woody biomass gas, and syngas which have recently been promoted make combustion more unstable. Especially, we focused on hydrogen-rich combustion of natural gas in this study. Since hydrogen does not emit CO_2 at all when it is burned, the hydrogen-containing combustion reduces CO_2 emissions. Therefore, we examined the influence of hydrogen ratio contained in the fuel on combustion instability experimentally and analytically.

A. Uemichi (✉) · I. Kanetsuki · S. Kaneko
Department of Mechanical Engineering, The University of Tokyo,
7-3-1 Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan
e-mail: uemichi@fiv.t.u-tokyo.ac.jp

© Springer Nature Singapore Pte Ltd. 2019

Y. Zhou et al. (eds.), *Fluid-Structure-Sound Interactions and Control*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-10-7542-1_56

2 Combustion Oscillation Experiment

The experimental equipment modeling on a micro gas turbine combustor was used [2]. For the fuel, Japanese town gas, 13A, which is equivalent to natural gas and hydrogen was used. The mixed fuel is injected into the combustor through the fuel supply pipe and then mixed with air at the swirler which has a function of a flame stabilizer simultaneously. For pressure fluctuation measurement, a pressure sensor installed on the bottom of the combustor was used. The hydrogen content in the fuel was varied from 0 to 40% in increments of 10%. Air is supplied by the compressor and a throttle to suppress pulsations in the air supply pipe is installed upstream of the swirler (see Fig. 3). Then, the experiment was carried out by decreasing the equivalence ratio starting from stoichiometric ratio down to the ratio corresponding to the extinction point by changing the fuel flow rate and air flow rate adjusting the total flow rate becomes constant of 15 L/s.

In this study, we treated the oscillations after reached the limit cycle. First, to examine the occurrence of combustion oscillation, the root-mean-square RMS = $\sqrt{\sum_{i=1}^{N} (p_i - \bar{p})^2 / N}$ (N: total number of samples, p_i: pressure of ith sample, $\bar{p}$: average pressure) values of pressure fluctuation were calculated as shown in Fig. 1. Regarding the range of RMS value, variable range does not show much difference regardless the change of hydrogen content in the fuel. Next, to further understand the characteristics of combustion oscillation, the FFT analysis was performed and measured oscillating frequencies are shown in Fig. 2. In the case of 13A 100%, the oscillation frequency around 350 Hz is observed excluding the case of the equivalence ratio around 0.6 corresponding to the extinction point. In 13A 100% case, it should be noted that near the extinction point, the single low-frequency oscillation

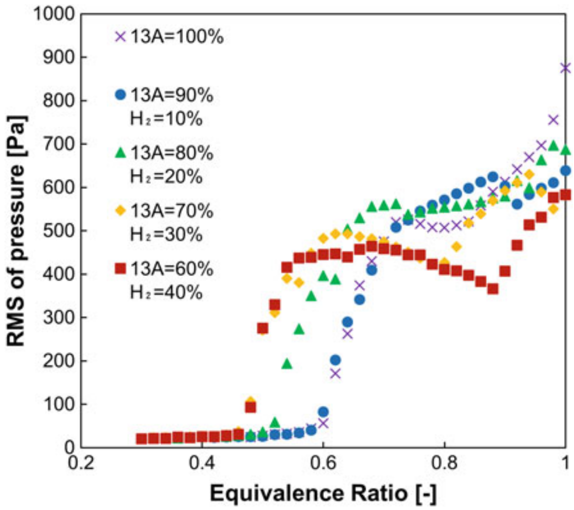


Fig. 1 RMS of pressure at the bottom face of the combustor

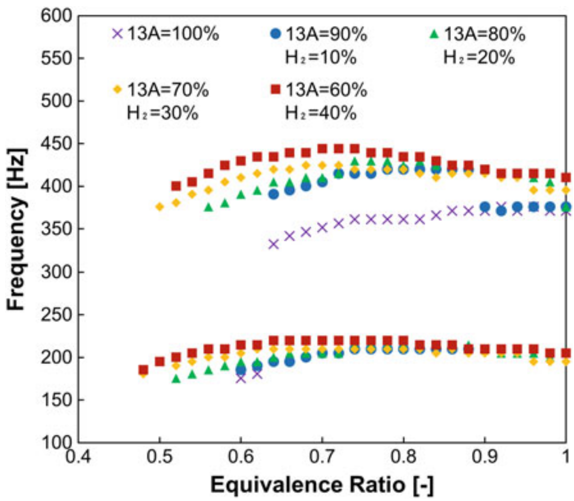


Fig. 2 Measured oscillating frequencies for various fuel mixtures

around 170 Hz was observed because the combustion field has changed near the extinction point. Whereas in the case of the mixture fuel of natural gas and hydrogen, double oscillating frequencies around 200 and 400 Hz are observed.

The oscillating frequency obtained by a simple calculation using the different diameter one-dimensional pipe modeling only the combustion chamber part where the acoustic boundary conditions are one end closed and the other end open is around 350 Hz. It is almost identical to the measured oscillating frequency with the case of only natural gas. However, we could not explain why different double frequencies of 200 and 400 Hz were measured in the case of hydrogen-containing fuel. Then, the oscillating frequencies in the hydrogen-containing case is thought to be the result of acoustic boundary condition change and we decided to investigate the acoustic impedance of acoustic system including the upstream part of the swirler.

3 Measurement of Acoustic Impedance and Acoustic Analysis

To examine the reason of the multiple frequencies observed in the combustor, the acoustic analysis was carried out. Thus, to improve the one-dimensional acoustic analysis, the acoustic impedance of the bottom of the combustor was measured experimentally [3] based on an acoustic network model [4, 5].

In the experiment, the transfer matrix method to measure acoustic impedances is selected, and the frequency range is determined by JIS A1405. Figure 3 shows the schematic of measurement apparatus. As shown in the figure, in the measurement, a loudspeaker supplies acoustic signals generated by a function generator. Then, the

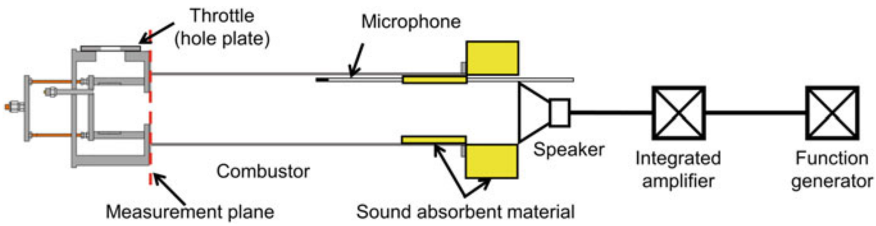
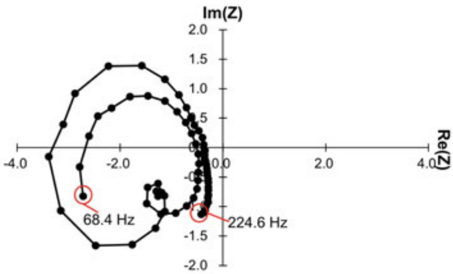


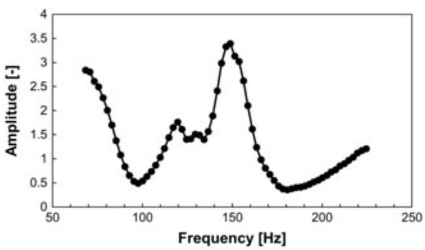
Fig. 3 Schematic image for acoustic impedance measurement

reflected acoustic signals are detected by a microphone. To eliminate the exterior noise, sound absorbent material is attached at the end of the combuster.

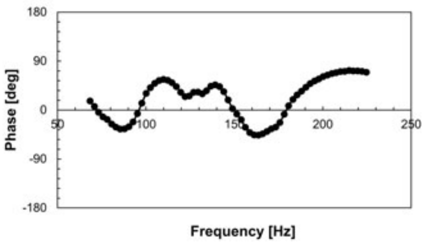
Figure 4 shows the acoustic impedance measured under room tempatature. Figure 4a–c show Nyquist plot on the complex plane, gain and phase of the measured acoustic impedance, respectively. As shown in Fig. 4b, a point of a peak where absolute amplitude becomes maximum is around 165 Hz. To accommodate the burned condition based on the unburned situation, the acoustic impedance correction is indispensable. Using the adiabatic flame temperature calculated by CHEMKIN-PRO, the oscillating frequency under burned condition can be estimated around 400 Hz which is 2–3 times of the original frequency under unburned condition; therefore, it is supposed that the throttle located at the upstream of the



(a) Nyquist plot on the complex plane (Starting point: 68.4 Hz, end point: 224.6 Hz)

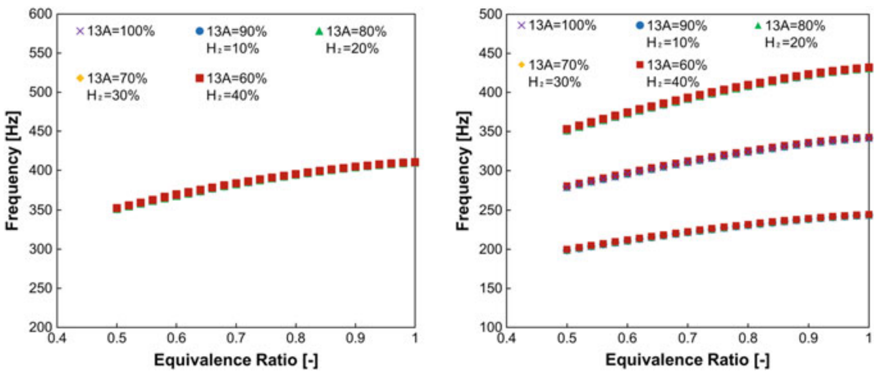


(b) Gain



(c) Phase

Fig. 4 Measured acoustic impedance



(a) Without the acoustic boundary conditions treatment.

(b) With the acoustic boundary conditions treatment.

Fig. 5 Calculated oscillating frequencies

swirler is the end of the oscillating mode around 400 Hz. Thus, the acoustic boundary conditions were changed by adding hydrogen to the fuel mixtures.

To obtain the oscillating frequencies under burned condition, the one-dimensional acoustic analysis taking account of acoustic impedance were carried out. Since the sound speed is a function of the square root of temperature T, temperature corrected acoustic impedance Z_c can be expressed as $Z_c = f\left(T^{-0.5}\right)$. Therefore, impedance Z_c is very much affected by the accuracy of T. Figure 5 compares the acoustic analysis results between those with and without the acoustic boundary condition which was derived by the measured acoustic impedance. In this calculation, the homogeneous adiabatic flame temperature in the combustor was considered. As a result, in addition to the oscillating frequency of around 350 Hz, the measured frequencies of around 200 and 400 Hz are obtained. It is noted that the acoustic impedance could reproduce the measured oscillating frequencies. However, the difference of the hydrogen content in the fuel mixture is not well expressed in this figure. Furthermore, the reason why the impedance change leads to the frequency change is not revealed. Therefore, other factors influenced by fuel components such as the flame position, the temperature distribution, and the gas properties including the heat capacity should be considered in the further research.

4 Conclusion

In this paper, to understand the combustion oscillation characteristics of hydrogen-rich fuel with natural gas, the experiments and the acoustic analysis were performed. For the acoustic analysis, the acoustic impedances were measured. As a result, employing the acoustic impedance as the acoustic boundary condition made it possible to express the different oscillating frequencies; therefore, adding hydrogen to the fuel changes the acoustic boundary conditions.

Acknowledgements This work was supported by JSPS Grand-in-Aid for Scientific Research (B) KAKENHI Grant Number 26289053.

References

1. Lieuwen TC, Yang V (2005) Combustion instabilities in gas turbine engine. American Institute of Aeronautics and Astronautics, Inc. https://doi.org/10.2514/4.866807
2. Adachi S, Iwamoto A, Hayashi S et al (2007) Emission in combustion of lean methane-air and biomass-air mixtures supported by primary hot burned gas in a multi-stage gas turbine combustor. Proc Combust Inst 31(2):3131–3138. https://doi.org/10.1016/j.proci.2006.07.239
3. Kato S, Fujimori T, Kobayashi H (2008) Effect of acoustic impedance on one-dimensional linear analysis of combustion oscillation in premixed gas turbine combustor. J Combust Soc Japan 50:72–80 (in Japanese)
4. Han X, Hui X, Qin H et al (2016) Effect of the diffuser on the inlet acoustic boundary in combustion-acoustic coupled oscillation. In: ASME Turbo Expo 2016, June 13–17, 2016 Seoul, South Korea. https://doi.org/10.1115/gt2016-57046
5. Polifke W (2004) Combustion instabilities. VKI Lecture Series