Partial Flame Analysis for Dynamic Characteristics of GCH4-GO2 Jet-swirl Coaxial Injector under Acoustic Perturbation

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1 Introduction

In order to achieve the high reliability of space missions, identifying and preventing possible hazards at each component is required from the course of development and research. These risks of failure could be found throughout all process, including liquid engines, solid boosters, avionics, stage separation, and satellite orbiting. However, according to statistical studies on the causes of space launch vehicle failure, problems in the engine propulsion process were found to be the most common reason[1-3]. Because the high stability of rocket engines is an important performance factor along with their combustion efficiency, many instability studies have been conducted on rocket engines and internal combustion processes [4-8].

Meanwhile, in premixed combustion instability research field, the Flame Transfer Function(FTF) is one of the most commonly used techniques for both of actual engine systems and fundamental flames. Applying artificial perturbation to the flame (propellant flow rate or equivalent ratio perturbation), the flame response could be contributed to detecting and predicting the operation environment where the flame becomes unstable[7,8]. In this study, a method similar to the Flame Transfer Function is applied to a lab-scale single injector non-premixed flame to analyze the flame response to the propellant acoustic excitation. In particular, the flame response analysis method for the entire and local parts of the flame at the University of Pennsylvania[9] is expanded to analyze the difference in results from the flame

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response measurement scheme. Additionally, the role of the fuel feeding line in the excitation response of the flame is confirmed.

2 Experimental Apparatus and Condition

Figure 1 is showing a jet-swirl model rocket injector for the ambient pressure GCH_4/GO_2 flame. Gas methane is injected from the center in a jet flow, and gas oxygen is introduced from annular path. In addition, gaseous oxygen is supplied in the form of a swirl through 4 tangential holes near the injector outlet, as shown in Fig. 2. In order to simulate unstable conditions of a rocket engine in operation, the central gas methane is modulated by a speaker. In this study, the fuel feeding line length(L) is defined as the length from the point where gas methane meets the speaker to the location where the methane path diameter decreases rapidly inside the injector. Table 1 lists the design parameters of the injector diameter, tangential hole diameter, recess length, and the gap distance.

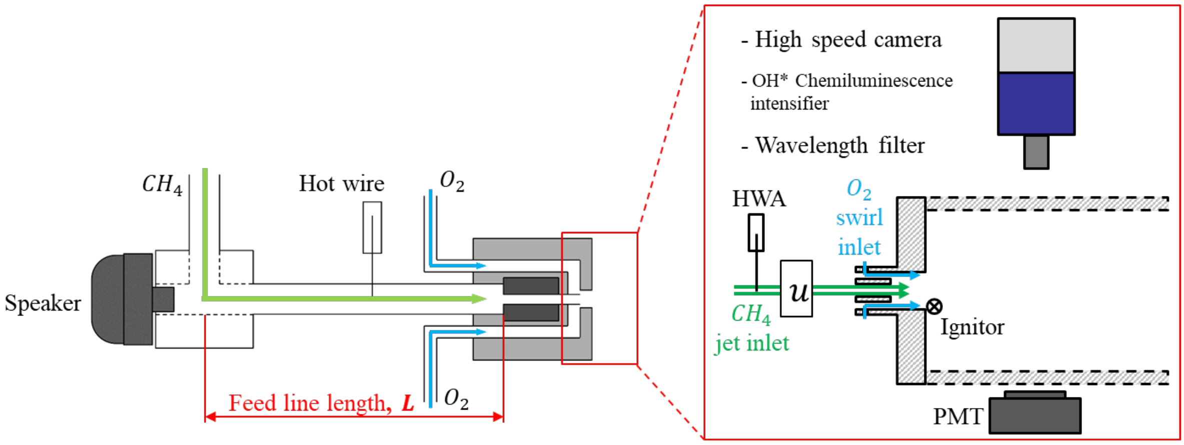

Figure 1: Schematics of jet-swirl GCH4-GO2 model injector and OH* signal measurement devices(high speed camera and PhotoMultiplier Tube, PMT)

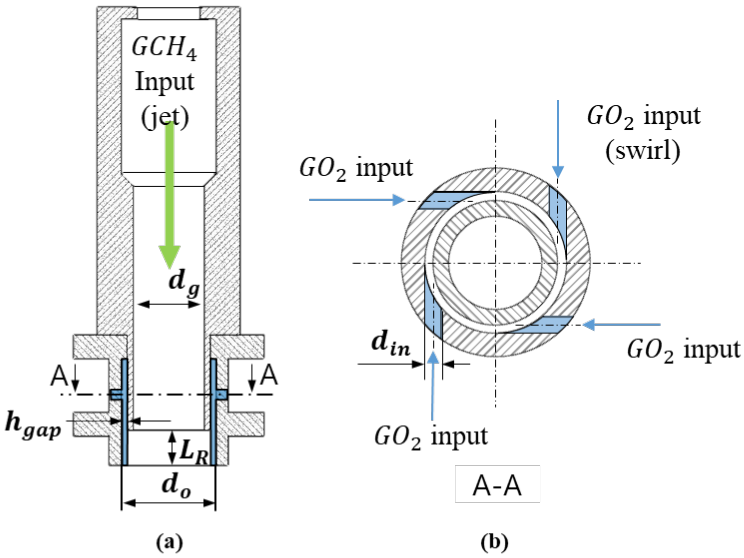

Figure 2: The design parameters: (a) near the injector exit and (b) the GO_2 tangential swirl hole

To observe the flame movement and perturbation, the OH* chemiluminescence signal is obtained via those two methods: a PhotoMultiplier Tube(PMT) and a high speed camera with OH* wavelength filter. The frame rate of the high speed camera is set as 5k Hz, and for synchronization of the PMT data with the high speed images, the PMT sampling rate is 50k Hz. A kind of Dirac delta signal is given when the camera operates, and then the PMT signal which is followed by the pulse signal is extracted. With above methods, the flame image and PMT signal could be captured simultaneously. Because the high speed images have the OH* signal intensity at each pixel(a point of the flame), FTF of a partial interest position of the flame could be plotted for each modulation frequencies. And the partial(or local) FTF is compared to the FTF from the PMT data, which represents the entire flame response.

Table 1 contains the experimental conditions of this study. Gas methane and gas oxygen have flow rates of 14.1 and 41 slpm, respectively, and the O/F ratio thereof is 6. The length of the gas methane feeding line changed with a uniform interval of 123 mm from 246 mm to 738 mm. The methane is excited with the frequency range from 60 Hz to 1000 Hz, and the excitation level was limited to 10% of the bulk velocity of the methane.(20 Hz intervals from 60 to 500 Hz and 50 Hz intervals from 550 to 1000 Hz)

Table 1: Experimental conditions

GCH_4 mass flow rate	14.1 [slpm]
GO_2 mass flow rate	41 [slpm]
O/F ratio	6
GCH_4 feeding linelength, L	246, 369, 492, 615, 738 [mm]
Perturbation frequency	60 - 1000 [Hz]

3 Results and Discussion

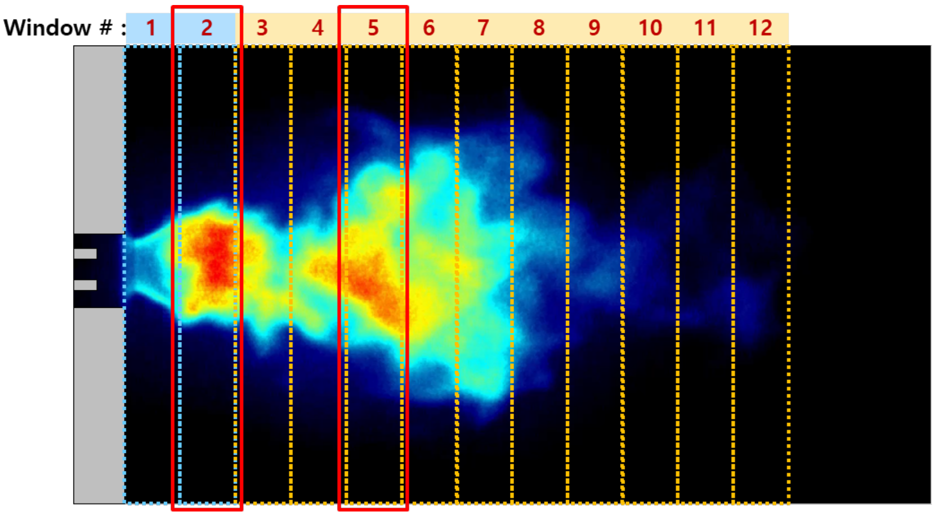

Figure 3: Spatial classification of interest windows on flame

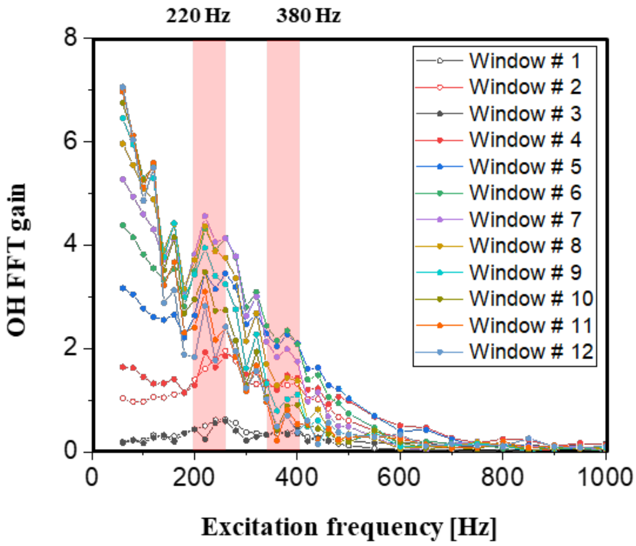

Figure 4: Acoustic response of flame to perturbation frequencies along interest windows

Figure 3 is a local interest area divided into a total of 12 parts according to the location of the flame. Fig.4 is an acoustic response graph for each frequency with the FFT(Fast Fourier Transform) gain value of the flame OH* chemiluminescence signal measured at each interest window set in Fig.3. The result in Fig. 4 is of the gas methane feeding line length $L = 246\ mm$. The 12 windows are divided into two groups overall based on the response tendency with flame, as distinguished by color in Fig.3.

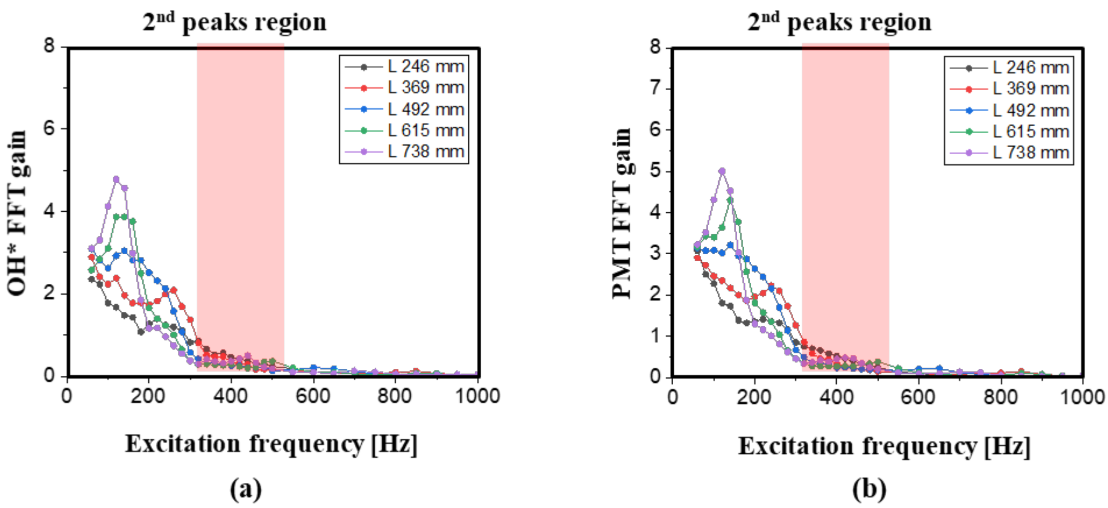

Figure 5: The entire flame signal response along excitation frequencies, (a) OH* chemiluminescence signal of overall window and (b) the PMT signal.

According to Fig.4, the response characteristics changed according to the position inside the flame. This means that if the acoustic response is measured based on the entire flame signal, the different response characteristics at each location of the flame could overlap. Consequently, the dynamic response could be changed. This could also be confirmed in the graph showing the OH* chemiluminescence signal perturbation magnitude of the united all interest windows and PMT signal along the modulation frequencies, shown in Fig.5. The FFT magnitude peak at 260 Hz and 400 Hz, which is confirmed in Fig.4, indicates that the flame movement is amplified under this frequency excitation. However, those peaks became blunt clearly in Fig.5. This attenuation of the perturbation signal was coincident in the results of other cases with the various methane feeding line length L.

It could be concluded that these above results occurred when the flame was separated due to the GCH_4 modulation with a speaker. As the methane flow rate decreases, the flame is divided into two clusters. The attached flame cluster near the injector exit contracts in the direction of the injector face plate, while the separated second cluster moves in the original direction. As these two flames progress in different directions each other, the phases of the flame signal change according to the flame position. These differences cause destructive interference against each other, resulting in different characteristics of the acoustic response measurement for the entire flame compared to the local dynamics for each location.

4 Conclusion

In this study, a jet-swirl GCH_4/GO_2 model rocket injector flame is investigated. A flame acoustic response is analyzed along external perturbation on the center jet GCH_4 flow. The dynamic characteristics measurement scheme was simultaneously compared with two methods: the local flame signal from a part of high speed OH* image, and the global data from the entire image and PMT data. Those two methods showed different results, showing the diminished flame fluctuation magnitude in the latter strategy, especially in the high frequency(2^{nd} peak).

Through the above experimental results and analysis, it could be found that in the flame combustion dynamics study, the method of measuring the partial flame signal is more useful for analyzing the dynamic characteristics of the flame than the entire flame. This is consistent with the advantages of local flame signal measurements which is verified in previous study[9], based on experimental. Furthermore, this study is meaningful in that the mechanism by which the response characteristics of the entire flame and the local flame have difference is identified by analyzing the shape and structure of the flame flow.

5 Acknowledgement

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References

[1] CROSS, Robert B.; VESELY, William E. Synthesizing a New Launch Vehicle Failure Probability Based on Historical Flight Data. 2018.

[2] FERNÁNDEZ, Lucía Ayala; WIEDEMANN, Carsten; BRAUN, Vitali. Analysis of Space Launch Vehicle Failures and Post-Mission Disposal Statistics. Aerotecnica Missili & Spazio, 2022, 101.3: 243-256.

[3] FERNÁNDEZ, L. Ayala; WIEDEMANN, Carsten; BRAUN, Vitali. Analysis of Space Launch Vehicle Failures. In: XXVI International Congress 31st August–3rd September 2021 On-line event hosted by the Tuscany AIDAA Section in Pisa. 2022.

[4] PARK, Gujeong, et al. Characteristics of gas-centered swirl coaxial injector with acoustic excitation of gas flow. AIAA Journal, 2017, 55.3: 894-901.

[5] BAE, Jinhyun; JEONG, Seokgyu; YOON, Youngbin. Effect of delay time on the combustion instability in a single-element combustor. Acta Astronautica, 2021, 178: 783-792.

[6] JO, Hyeontaek, et al. Dynamic behavior of jet-swirl spray under resonance condition with external excitation. Acta Astronautica, 2021, 189: 298-309.

[7] CANDEL, Sébastien, et al. Dynamics of swirling flames. Annual review of fluid mechanics, 2014, 46: 147-173.

[8] POINSOT, Thierry. Prediction and control of combustion instabilities in real engines. Proceedings of the Combustion Institute, 2017, 36.1: 1-28.

[9] KIM, Kyu Tae, et al. Spatially distributed flame transfer functions for predicting combustion dynamics in lean premixed gas turbine combustors. Combustion and Flame, 2010, 157.9: 1718-1730.