공학석사학위논문

A Study on Combustion Instability Analysis of Partially Premixed Model Gas Turbine Combustor with 1D Lumped Method

1D Lumped Method를 이용한 모형 부분 예혼합 가스터빈 연소기의 연소불안정 해석

2017년 2월

서울대학교 대학원

기계항공공학부

김 정 진

Abstract

A Study on Combustion Instability Analysis of Partially Premixed Model Gas Turbine Combustor with 1D Lumped Method

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Recently, fine dust generation in the East Asian region has been emerging as a serious problem in each spring. It is expected that the strategy of increasing the weight of the combined cycle power plant, which is an environmentally friendly type of power generation, will play a big role in reducing fine dust. Gas turbines that use various renewable fuel such as syngas, synthetic natural gas (SNG), and biogas are being steadily developed, as it is effective not only to reduce fine dust but also to reduce exhaust emissions. Also, partially premixed gas turbine combustor is basically designed as a lean burn and has the possibility of manifesting combustion instability phenomenon. Therefore, it is important to understand and predict combustion instability characteristics for various fuel compositions in gas turbine combustor development.

The purpose of this study is to analyze the instability characteristic of partially premixed combustor according to combustor length, flame position and fuel composition using 1D lumped method. In addition, the prediction of the instability mode shifting, which is the unique phenomenon of partially premixed combustor, is conducted for the first time. As a study procedure, Flame Transfer Function (FTF) in various fuel compositions are obtained with photomultiplier tube (PMT) and hot wire anemometry (HWA). Then the length of the combustor and the position of the flame obtained through the OH-PLIF image were adjusted. In addition, the thermal properties for various fuel compositions were applied using the NASA's CEA code.

The predictions of instability frequency of dominant longitudinal mode and multimode instabilities were similar to those of experimental results. As the length of the combustor increases, a decrease in the combustion instability frequency and a change in the instability mode are were predicted. Also, by analyzing the combustion instability characteristics according to the flame position, it is confirmed that the instability mode shifting phenomenon can be predicted only by the change of the flame position under the same FTF and fuel/air condition. In the overall fuel composition, the instability mode was predicted to increase as the percentages of H_2 fuel composition increased, as in the combustion instability mode shifting phenomenon that occurred in the combustion experiments. Prediction of instability frequency and instability amplitude trends were improved by applying combustor temperature and reflection coefficient of experiment. Based on these results, it is possible to predict the instability amplitude tendency and suggest the direction to avoid instability during design and operation.

Keywords: Combustion instability, 1D lumped method, Flame transfer function, Partially premixed combustor, Combustion instability prediction, Instability mode shifting phenomenon, Multimode instability

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CHAPTER 1

INTRODUCTION

1.1 Gas Turbine of the Combined Cycle Power Plant

Recently, fine dust generation in the East Asian region has been emerging as a serious problem in each spring. In particular, on June 3, 2016, the Korean government announced a plan to deal with the high-concentration of fine dust in the Korea [1]. The government's fine dust plan specifies the reduction of coal fired power plants which are the cause of fine dust and the fosterage of renewable energy industries.

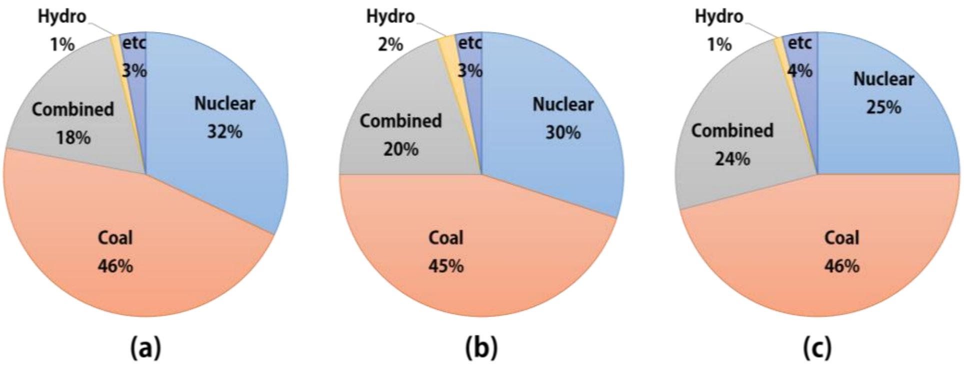

Figure 1.1 Power generation ratio from Major Electric Power Statics: (a) 03.2016, (b) 07.2016, and (c) 11.2016 (ref. [2]).

According to Figure 1.1, the power generation ratio of gas turbines, which accounted for 18% of the total power generation in March 2016, increased to 20% in

July 2016 after the announcement of the government special plan for fine dust. This is an increase of about 23% compared to the March 2015, and power generation ratio of gas turbine has steadily increased until November 2016. A strategy to increase the weight of a combined cycle power plant, an environmentally friendly type of power generation, is expected to play a major role in reducing fine dust. The development of low-NOx combustors that can use various types of fuels such as syngas, synthetic natural gas (SNG), and biogas and that is effective not only in reducing fine dust but also exhaust gas is underway the domestic and international markets.

1.2 Combustion Instability

A low-NOx combustor is basically designed as a lean burn, which may cause combustion instability phenomenon. The combustion instability is a phenomenon in which the perturbation increases nonlinearly when the heat release perturbation and acoustic perturbation inside the combustor are in phase through the feedback loop. As shown in figure 1.3, combustion instability of gas turbine will adversely affect not only the combustor failure but also the downstream part, resulting in a disruption of the stable power supply [4].

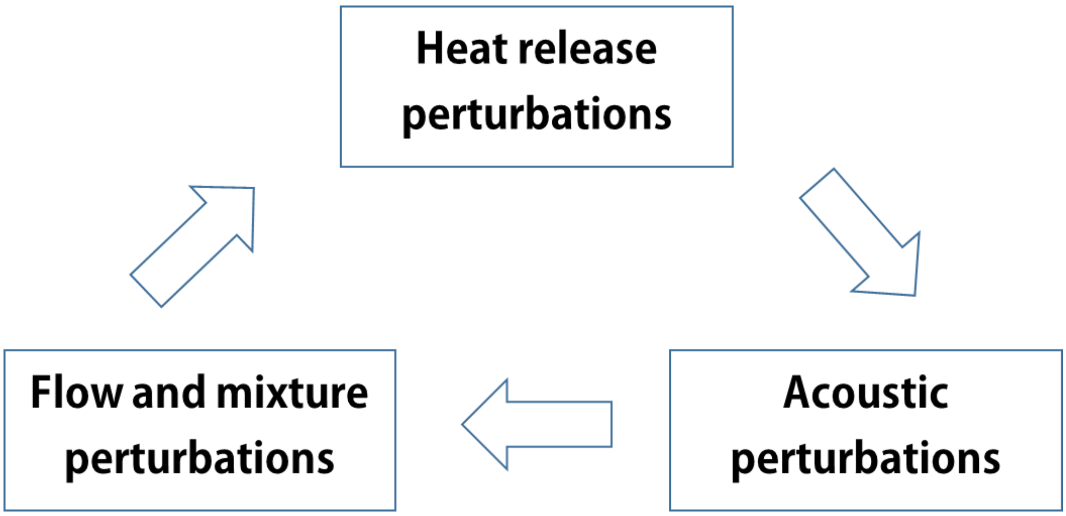

Figure 1.2 Combustion instability feedback loop diagram (ref. [3]).

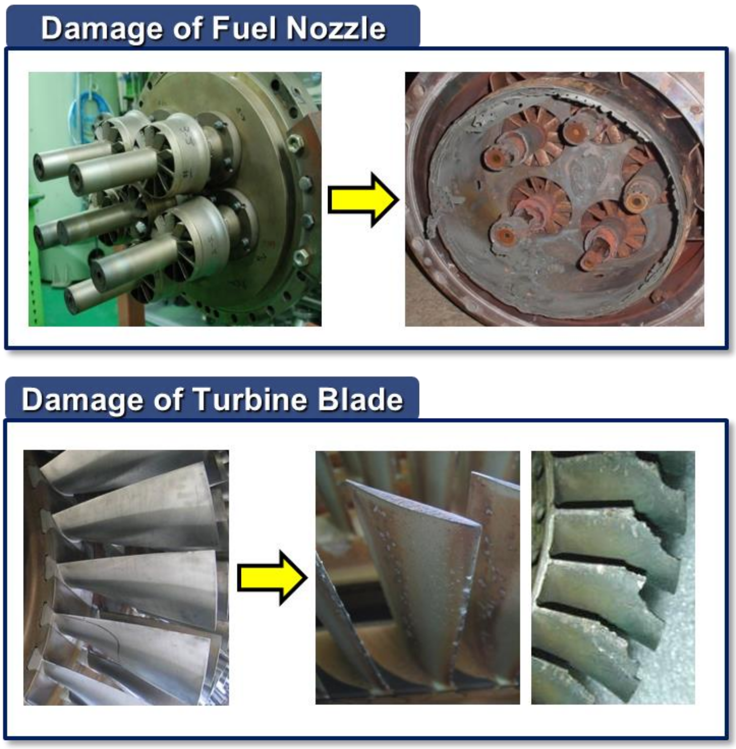

Figure 1.3 Adverse effects of combustion instability on the gas turbine.

The mechanism of the combustion instability phenomenon has been studied with time-lag analysis [5, 6], flame-vortex interaction [7, 8], entropy perturbation [9, 10], processing vortex core [11, 12]. As a previous study, our research group selected partially premixed combustor which has low probability of flashback even when the percentages of H_2 fuel composition increased, and conducted combustion instability experiments in various fuel compositions using H_2, CH_4, and CO mixture gas [13]. The experimental results show that combustion instability occurs in H_2 and CH_4 fuel compositions. Furthermore, as the percentages of H_2 fuel composition increases, there is an instability mode shifting phenomenon in which the instability frequency increases step by step.

Next, our research group focused on the H_2 and CH_4 fuel composition, which was predominantly combustion unstable, and conducted combustion experiments [14]. As a result, the shifting in the longitudinal instability mode was reaffirmed as the percentages of H_2 fuel composition increased. The instability frequency was interpreted by using the concept of convection time obtained by unburned mixture length measured by OH-PLIF image. Finally, the mechanism of the instability mode shifting phenomenon is explained through the inverse proportionality between the instability frequency and the convection time. This result shows that convection time obtained by unburned mixture length are major factors in the combustion instability mode shifting phenomenon of the partially premixed combustor.

1.3 Prediction of Combustion Instability

It is important to understand combustion instability characteristics for various fuel compositions in gas turbine combustor development. In particular, if the combustion instability phenomenon can be analyzed and predicted, it is possible to design a combustor that avoids the conditions in which the combustion instability phenomenon occurs in advance, or to effectively avoid the combustion instability condition that occurs during operation. Various studies have been carried out to predict the combustion instability such as the lower order model [15], the direct method (RANS, LES) [16], the linearized equations in time domain [17], and the Helmholtz solver [18].

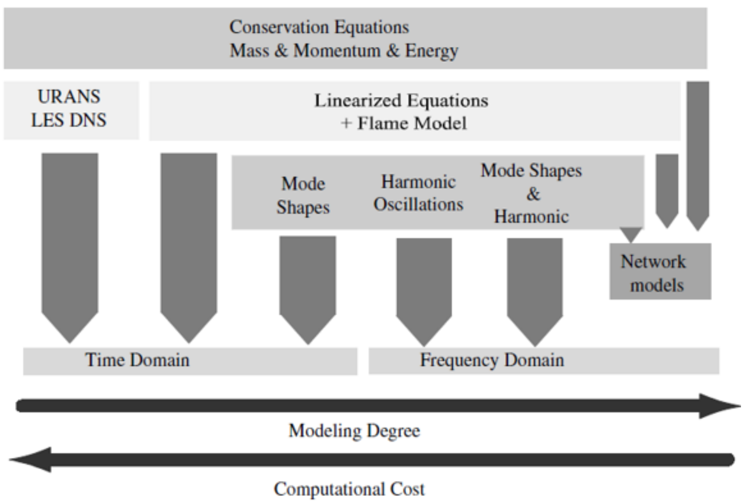

Figure 1.4 Methods for prediction of combustion instability.

One example of the lower order model is the open source code, OSCILOS, based on the 1D lumped method. OSCILOS is a code developed by the A. S. Morgans group at Imperial University in England to predict combustion instability in the frequency domain and time domain. They obtained the Flame Describing Function (FDF) using the OpenFOAM PaSR tool only with the geometry information of the combustor, and confirmed that the predicted value by OSCILOS agrees with the experimental value of the experimental instability frequency [15]. In Korea, Cha et al., used the OSCILOS and the experimental data of the Santavicca group's premixed gas turbine combustor to predict the combustion instability according to the change of combustor length and boundary conditions [19]. However, previous studies have focused mainly on the prediction of single instability frequency, and prediction of instability mode shifting phenomena have not been performed.

The purpose of this study is to analyze the instability characteristics of partially premixed combustor according to combustor length, flame position and fuel composition using 1D lumped method. In addition, the prediction of the instability mode shifting, which is the unique phenomenon of partially premixed combustor, is conducted for the first time.

CHAPTER 2

APPARATUS AND EXPERIMENTAL METHOD

2.1 Flame Transfer Function Measurement System

In order to predict combustion instability through the 1D lumped method, flame transfer function (FTF) measurement must be preceded. The accuracy of the thermoacoustic model, such as the Helmholtz solver is strongly influenced by the heat release rate. The FTF, which can represent this heat release rate as a function of frequency, was obtained through experiments.

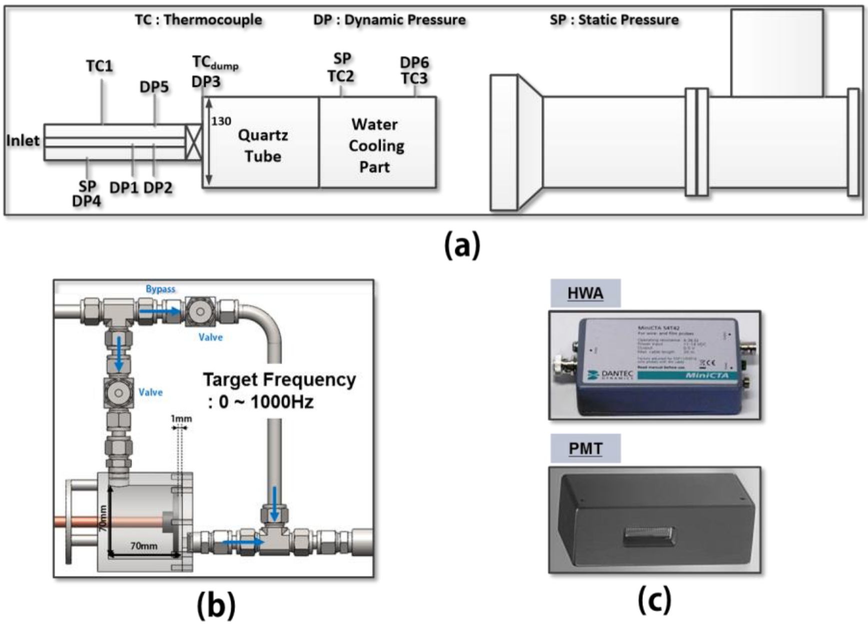

Figure 2.1 Measurement system for FTF: (a) schematic diagram of test rig, (b) flow modulation device on fuel line, and (c) HWA and PMT system.

Experimental setup for FTF measurement shown in Figure 2.1 consists of a combustor, a flow modulation device (Siren), a hot wire anemometry (Dantec, MiniCTA), and a photomultiplier tube (Hamamatsu, H7732-10). Combustion instability experiments were carried out in rigs with outlet of closed boundary conditions, but it was necessary to remove the influence of intrinsic acoustic wave interaction in the combustor for accurate FTF measurement. Therefore, the FTF was measured after the outlets were opened by separating the combustor and the exhaust duct, and a fan was installed at the rear end to prevent the unburned gas from flowing back into the separated space. The siren was installed at the front of the fuel line to perturb the fuel flow rate, and the fluctuation was limited to within 10% of the mean velocity. The quartz installed for visualization and photomultiplier tube (PMT) system were used to measure the heat release wave perturbation, and the flow rate perturbation in the fuel line was measured through the hot wire anemometry (HWA) system.

As a result, the gain and phase of the FTF are obtained in various fuel compositions, and tendency of the FTF for H_2 percentage of 25%, 50% and 75% is shown in Figure 2.2. The gain of the FTF decreased as the percentage of H_2 fuel composition increased. Also, the frequency at the peak of gain increased as the percentage of H_2 fuel composition increased. In the case of the phase, the decreasing gradient was reduced as the percentage of H_2 fuel composition increased.

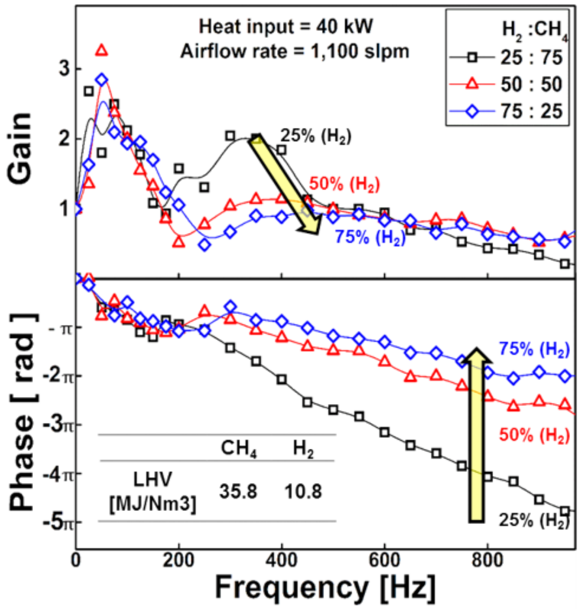

Figure 2.2 Measured FTF for H_2 percentages of 25%, 50% and 75% (ref. [14]).

2.2 1D Lumped Method with OSCILOS

The OSCILOS analyzes the combustion instability phenomenon based on the 1D lumped method with the structure shown in Figure 2.3. The combustor length, thermal properties, flame model and boundary conditions are set as input variables and the combustion instability is analyzed in the frequency domain. The 1D lumped method is based on two assumptions. First, only the longitudinal acoustic waves of the 1D plane are considered, assuming that the radial perturbation is negligibly smaller than that of the longitudinal acoustic waves. It is also assumed that the length of the flame is relatively short compared to the wavelength of the acoustic wave, so it is assumed to be thin flame. Through these assumptions, the combustion instability prediction is performed as follows. The combustor is divided into a plurality of modules and the thermal properties of each modules are continuous with respect to the boundary surface. Finding the thermal properties of each module that meets the governing equations with minimal error, a combination of instability frequencies and growth rates is obtained.

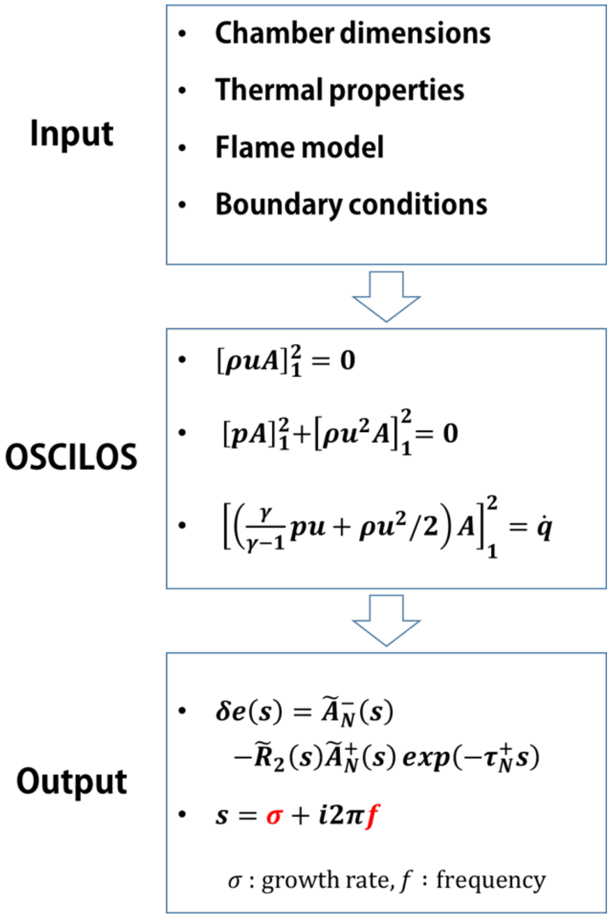

Figure 2.3 Software structure of OSCILOS.

2.2.1 Combustor Geometry

FTF data for the central annular swirling nozzle was obtained using the system as shown in the Figure 2.1 and combustion instability experiment of the test rig in the Figure 2.4 were performed. The combustor length can be varied from 1160 mm to 1400 mm by changing the position of the plug nozzle. A cooling system is applied during the combustion test to prevent overheating of the combustor due to heat. The quartz installed for flame visualization is cooled by air and the plug nozzle and the combustor are cooled by water. After the combustion tests were completed, the instability of the partially premixed combustor using the 1D lumped method was analyzed and predicted.

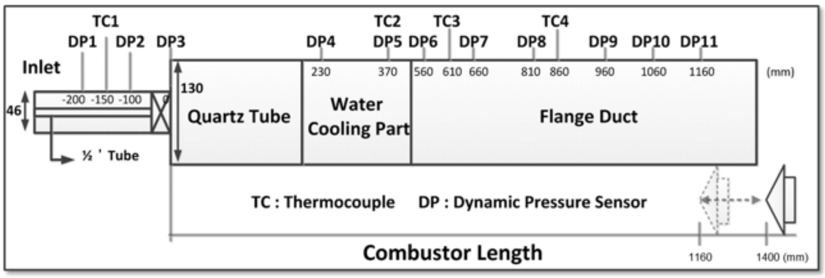

Figure 2.4 Schematics of the partially premixed model combustor.

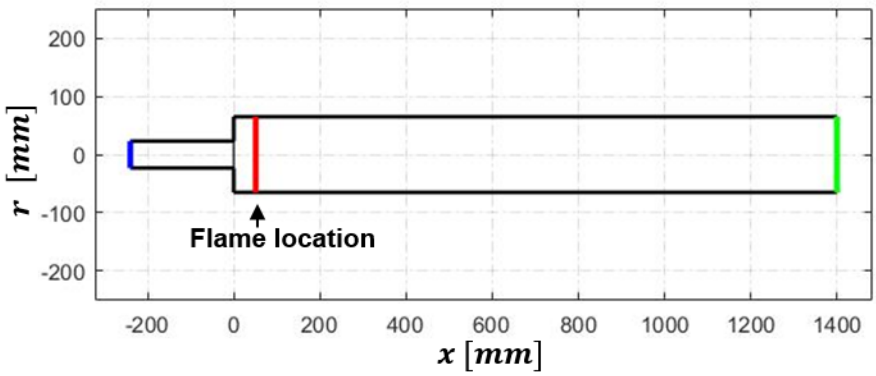

Figure 2.5 Schematics of the partially premixed model combustor modeling.

For the analysis and prediction through the 1D lumped method, the inlet, flame, combustor, outlet and boundary conditions are defined as shown in the Figure 2.5. The inlet of the rig is set based on the strainer installed to stabilize the flow, and the outlet of the rig is defined as the plug nozzle.

2.2.2 Flame Position

Yoon et al. presented the convection time as a major parameter in the combustion instability mode shifting phenomenon of partially premixed model combustor [14]. Unlike the case of the premixed combustor, the convection time depends on the distance from the dump surface to the flame surface, since the mixing length of the partially premixed combustor is relatively short. The 1D lumped method was developed for a premixed combustor, but the combustion instability was analyzed and predicted by controlling the flame position to make a significant change in convection time in the partially premixed combustor.

In this study, it was important to decide how to select the flame position that would have a large impact on the convection time. Two flame lengths, L_coi and L_ub, obtained through visualization were calculated to select the appropriate flame position for modeling. First, L_coi is calculated as the distance from the dump surface to the center of the intensity from the averaged flame image as shown in the Figure 2.6. These OH chemiluminescence images were obtained from an intensified charge-coupled device (ICCD) camera (Princeton Instruments, PI-MAX2), a UV lens (f/4.5), and a filter (WG-305, UG-11). Next, L_ub was calculated as the distance from the dump surface to the end of the unburned gas area from the averaged image as shown in the Figure 2.7. These OH PILF images were acquired with an Nd-YAG laser (Continuum, Surelite-I), dye laser (Continuum, ND-6000), an ICCD camera (Princeton Instruments, PI-MAX2), a UV lens (f/4.5), and a filter (WG-305, UG-11).

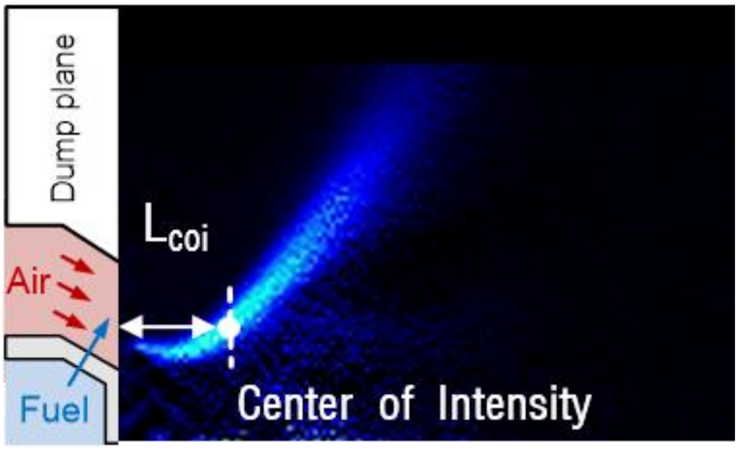

Figure 2.6 Average flame image measured by the OH chemiluminescence.

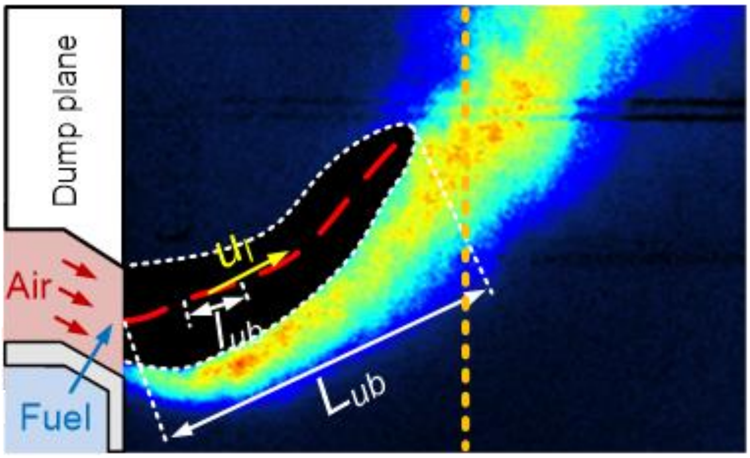

Figure 2.7 Average flame image measured by the OH-PLIF.

The results of the instability frequency prediction for the 25% H_2, 75% CH_4 fuel composition and 1400 mm combustor length condition are shown in the table 2.1 were used to determine the flame length to be applied to the flame position. Although L_ub is about 1% difference from the L_coi, it was used for combustion instability analysis and prediction because it had relatively less error. This result is because L_ub, the distance from the dump surface to the end of the unburned gas area, is a better representation of the convection time, which is a key factor in the combustion instability characteristics of a partially premixed combustor with a short mixing length.

Table. 2.1 Prediction of instability frequency according to flame position.

Parameter	***L_coi***	***L_ub***	**Experiment**
Length [mm]	35	51	-
Frequency [mm]	568	565	505
Error [%]	-12.5	-11.9	-

2.2.3 Thermal Properties

The 1D lumped method code is based on a premixed combustor, so there is no distinction between air and fuel line. Therefore, the thermal properties required for prediction were calculated in advance using the NASA's CEA code. It is set to match the thermal properties obtained from the partially premixed combustor experiment and is used in the prediction in the form of step function as shown in the Figure 2.8. The origin of the x-axis from the Figure 2.8 is the dump surface of the combustor.

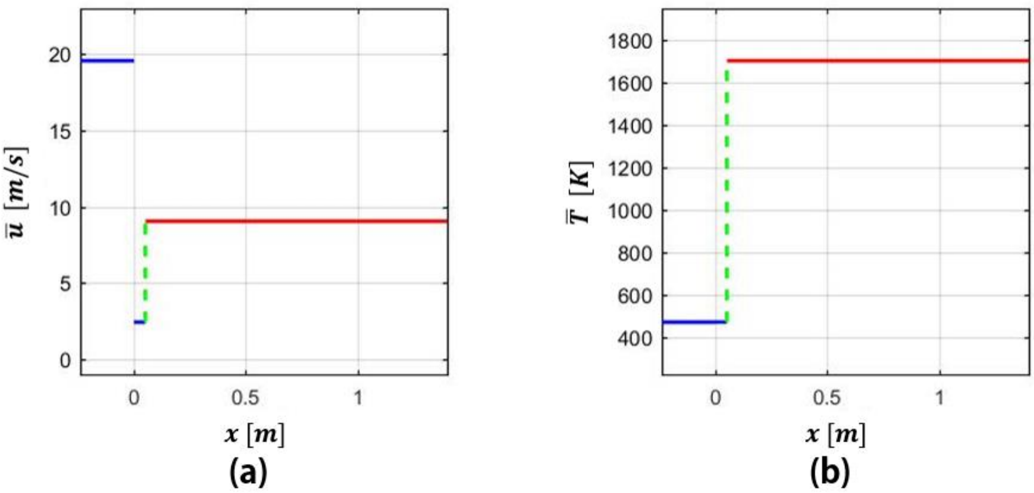

Figure 2.8 (a) velocity, and (b) temperature for 25% H_2, 75% CH_4 fuel composition.

2.2.4 Flame Model

FTF measurement must be preceded in order to predict combustion instability. The FTF expresses the relationship between the amount of acoustic perturbation and the amount of heat release perturbation. The FTF considered in this study is defined as Equation 2.1.

$$FTF(s) = \frac{\hat{q}(s)/\bar{q}(s)}{\hat{u}(s)/\bar{u}(s)} \tag{2.1}$$

The ratio of velocity fluctuations is measured by HWA and the ratio of heat release fluctuations is measured by PMT with OH* filter. Based on the measured data, the gain and phase of the FTF are calculated using Equation 2.2

$$Gain = |FTF(s)| \qquad\qquad Phase = tan^{-1}\left[\frac{FTF(s)_{im}}{FTF(s)_{real}}\right] \tag{2.3}$$

The gain and phase of the FTF were obtained for H_2 fuel composition (25-87.5%, span = 12.5%) which could be measured, and it was input into the following approximate Equation 2.3 as the flame model.

$$FTF(s) = \frac{b_1 s^{n-1} + b_2 s^{n-2} + \cdots + b_{n-1} s + b_n}{a_1 s^{m-1} + a_2 s^{m-2} + \cdots + a_{m-1} s + a_m} \tag{2.3}$$

In fact, more accurate combustion instability analysis requires a FDF that is a function of not only the frequency but also the velocity perturbation. However, due to the limitations of the experimental apparatus, the FTF is used as the flame model in this study.

In order to use the FTF results accurately, curve fitting using MATLAB code was applied. To maintain the characteristics of the FTF function measured by the experiment, the y intercept of the gain is held at 1 and the y intercept of the phase is fixed at zero. After curve fitting, the gain and phase of FTF was obtained each fuel composition condition, such as in the 25% H_2 fuel condition in the Figure 2.9 and are used for combustion instability analysis and prediction.

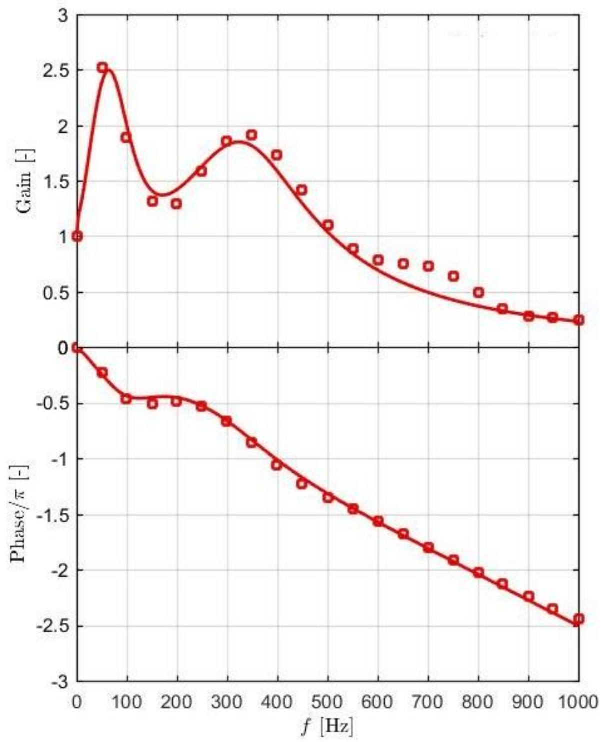

Figure 2.9 FTF for 25% H_2, 75% CH_4 fuel composition.

2.2.5 Boundary Condition

It is necessary to set the boundary conditions to predict the instability characteristic of the partially premixed combustor. The strainer, which is the reference of the inlet, is set to open boundary because it is open about 46% of the total area. In addition, the plug nozzles that make the acoustic boundary while adjusting the length of the combustor are taken as the closed boundary. In addition, boundary conditions of the inlet were applied similar to the experimental conditions, using the reflection coefficients obtained from the combustion experiments.

2.3 Test Condition for Prediction

As a comparative group, combustion experiments were previously carried out and combustion instability of the partially premixed combustor using 1D lumped method were analyzed and predicted. Test conditions for this study are shown in Table 2.2. Based on previous studies showing that instability mainly occurs in this fuel composition, a mixture of H_2 and CH_4 is used as fuel for the combustion instability test. The length of the combustor was varied from 1160 mm to 1400 mm at intervals of 30 mm, and the position of the flame was changed from 0 mm to 51 mm based on the dump surface. In addition, the volume flow rate of fuel was adjusted to vary the H_2 fuel composition from 12.5 % to 87.5 % (span = 12.5 %). Combustion experiments were carried out at the H_2 fuel composition from 0 % to 100%, but the fuel composition which could not obtain FTF due to limitations of measuring equipment was excluded. Basically, the volume flow rate of the fuel was determined under the condition that the air temperature was 473 K, the volume flow rate of the air was fixed at 1100 slpm and the heat input was always 40 kW.

Table. 2.2 Selected condition for prediction.

Parameter	**Value**
Fuel	H_2/CH_4
Heat input [kW]	40
Air temperature [K]	473
Air volume flow rate [slpm]	1100
Equivalence ratio	0.51~0.57
Combustor length [mm]	1160~1400
Flame position [mm]	0~51
H_2 percentages of fuel composition [%]	25~87.5

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Prediction of Instability with Combustor Length Variation

Combustion instability analysis was carried out with combustor length variation in the 25% H_2, 75% CH_4 fuel composition ratio. While the 1D lumped method is applied with the combustor length changed from 1160 mm to 1400 mm, the instability frequency can be obtained. The growth rate can be acquired for each instability frequency and can be displayed as shown in the Figure 3.1. If the growth rate is greater than 0, the combustion is unstable, and if the growth rate is less than 0, it can be regarded as a combustion stable region.

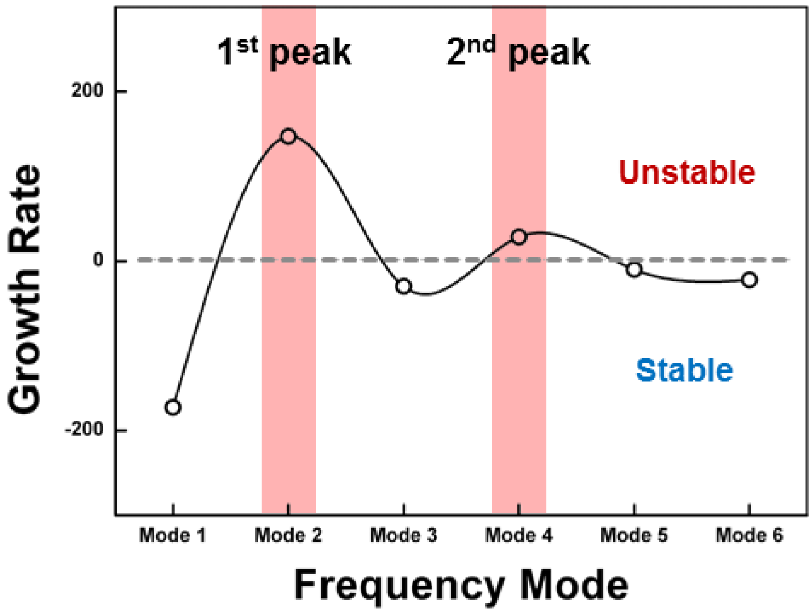

Figure 3.1 Possibility of combustion instability for frequency mode.

In addition, if two or more instability modes appear like red shaded bars as shown in the Figure 3.1, the mode with the largest growth rate is the dominant frequency band (1st peak) and the mode with the next largest growth rate is the 2nd peak. In the case of the experimental data of the previous study, only 0.15 psi (RMS value) or more was assumed to be the unstable region. But in this study, the absolute magnitude of the instability amplitude was not taken into consideration, since the peak was displayed without reference.

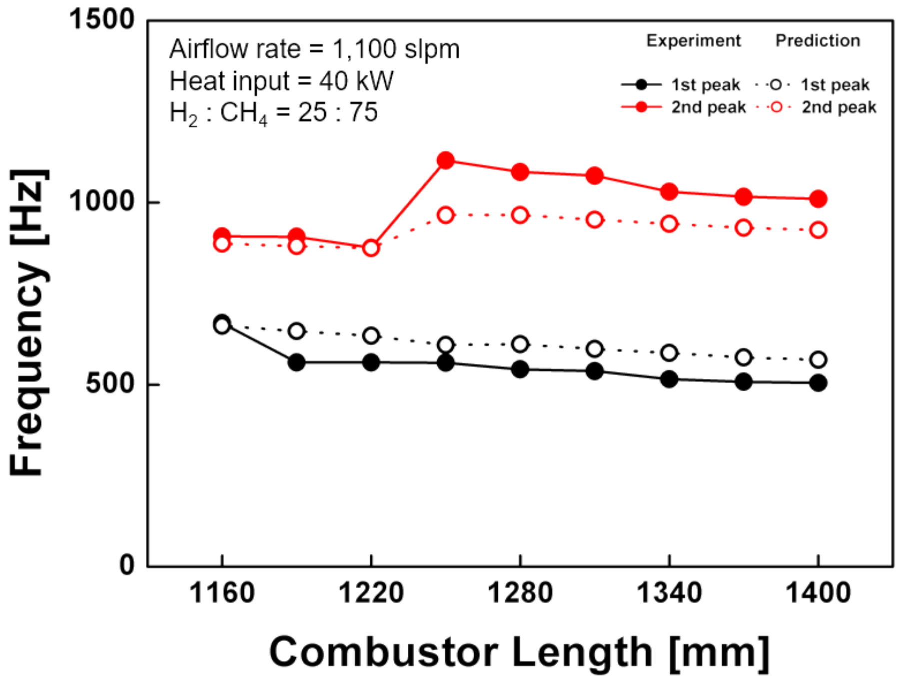

Figure 3.2 Prediction of instability frequency with combustor length variation.

The Figure 3.2 shows the tendency of the instability frequency according to the combustor length varied from 1160 mm to 1400 mm (span = 30 mm) in 25% H_2, 75% CH_4 fuel composition. As a result of comparing the predicted results with the experimental values according to the changes in the length of the combustor, it is confirmed that the dominant instability frequency decreases with increasing combustor length though there is an error of about 10%. Furthermore, it was clearly predicted that the dominant instability mode and the second strong mode coexist as in the condition where the multimode instabilities appeared in the experiment.

In addition, when the length of the combustor was increased, it was predicted that the 1st peak would be constant as the 2nd mode and that the 2nd peak would shift from 3rd mode to 4th mode at the combustor length of 1250 mm. This prediction tendency is the same as the experimental result, but the degree of the frequency prediction error was different before and after the mode shifting. This error may have been caused by the difference between the adiabatic flame temperature used in the prediction result and the temperature condition in the experiment.

3.2 Prediction of Instability with Flame Position Variation

When the fuel composition (25% H_2, 75% CH_4) and the air flow rate were fixed, the change of growth rate of each instability mode was examined arbitrarily changing the position of the thin flame from the flame length to the dump surface. As can be seen from the Figure 3.3, the growth rate of the 2nd mode, which was the dominant instability frequency, gradually decreased as the position of the thin flame became closer to the dump surface. On the other hand, the growth rate of the 3rd mode which was the second strong instability frequency, tended to increase.

In previous study, it was explained that the convection time due to the flame structure change causes the combustion instability shifting phenomenon [14]. This is due to the unburned mixture length which is main parameter for determining instability characteristic of the partially premixed combustor. In other words, it is confirmed that the instability mode shifting phenomenon can be predicted only by the change of the flame position under the same FTF and fuel/air condition.

In addition, the fuel composition is different, but can be compared with the instability mode analysis according to the equivalence ratio change in the previous experimental study (100% CH_4 fuel composition). As the equivalence ratio increases in the combustion experiments, it is confirmed that the unburned mixture length decreases and the combustion instability mode tends to increase, as shown in the Figure 3.4. The fact that the combustion instability mode shifting due to the reduction of the unburned mixture length is the same as the prediction, sufficiently supports the reliability of the prediction result.

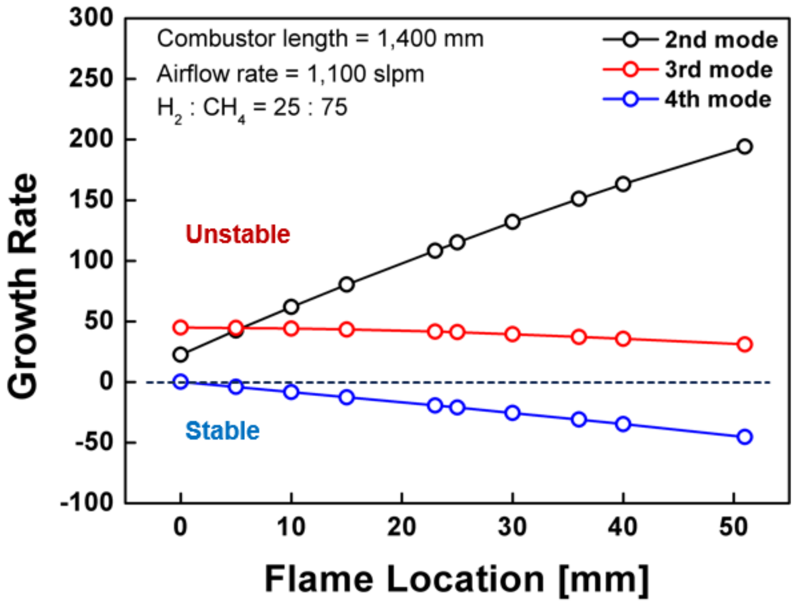

Figure 3.3 Growth rate for instability mode with flame position variation.

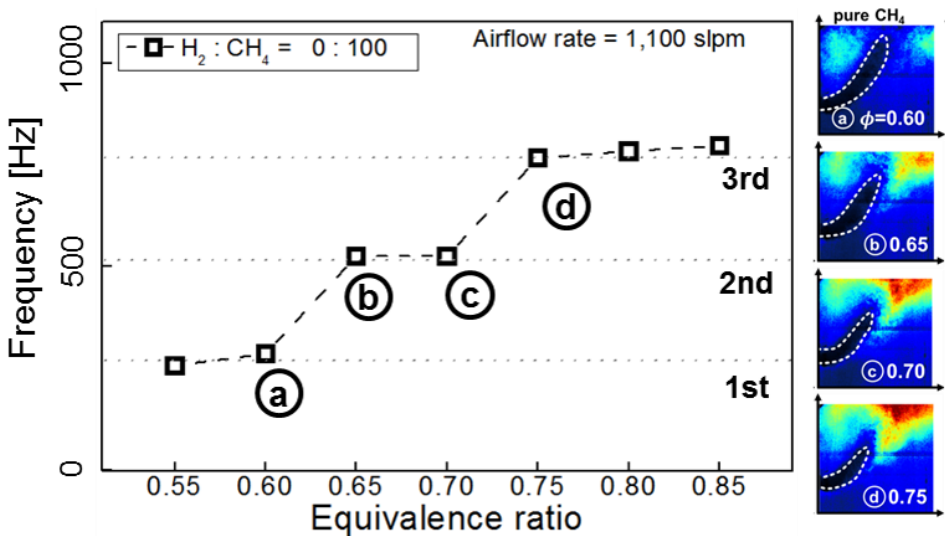

Figure 3.4 Experimental result of instability mode with equivalence ratio variation (ref. [14]).

3.3 Prediction of Instability with Fuel Composition Variation

The prediction was carried out by varying the fuel composition ratio for H_2 percentages of 25%, 50% and 75% at 1400 mm combustor length. As shown in the Figure 3.5, when the fuel composition ratio is 25% H_2, it is predicted that the dominant longitudinal instability frequency occurred in the 2^{nd} mode same as the result in combustion experiments. Also, it is confirmed that multimode instabilities occurred as same as the experimental results.

Continuously, it is predicted that instability occurs in 4^{th} mode for 50% H_2 fuel composition and 5^{th} mode for 75% H_2 fuel composition. As a result of instability analysis due to changes in the fuel composition ratio, there was the error in the prediction of the instability frequency and the dominant instability mode in the 75% H_2 fuel composition. Nonetheless, the prediction of the experiment tendency to increase the dominant instability frequency mode as the hydrogen ratio increases has been successful.

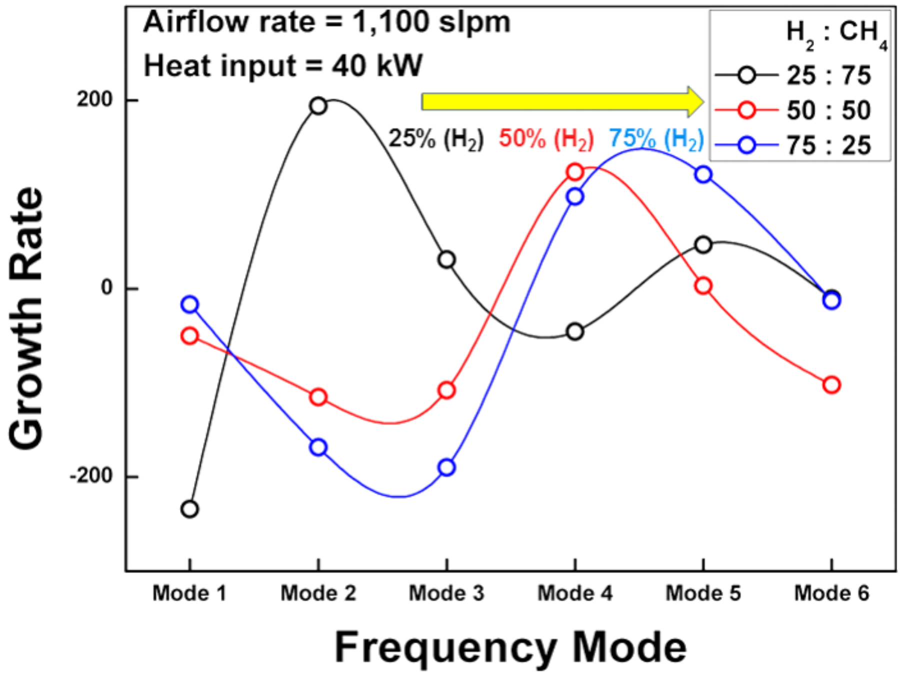

Figure 3.5 Growth rate for instability mode with fuel composition variation.

3.4 Prediction of Instability Mode Shifting Phenomenon

Prediction of the instability mode shifting phenomenon, which is one of the instability characteristic of the partially premixed combustor, was attempted in consideration of the flame position and the fuel composition in the combustor length of 1400 mm. The result in Figure 3.6 indicates instability frequency prediction from 25% to 87.5% H_2 fuel composition which can measure the FTF.

When the H_2 percentages of the fuel composition increases, the flame position is set closer to the dump surface as the unburned mixture length becomes shorter. In the overall fuel composition, multimode instabilities were exhibited and the instability mode was predicted to increase as the percentages of H2 fuel composition increased, as in the combustion instability mode shifting phenomenon that occurred in the combustion experiments. These predictions support the results of previous experimental studies that convection time based on the length of the unburned mixture in the partially premixed combustor is the main variable for determining the instability mode, unlike premixed combustor.

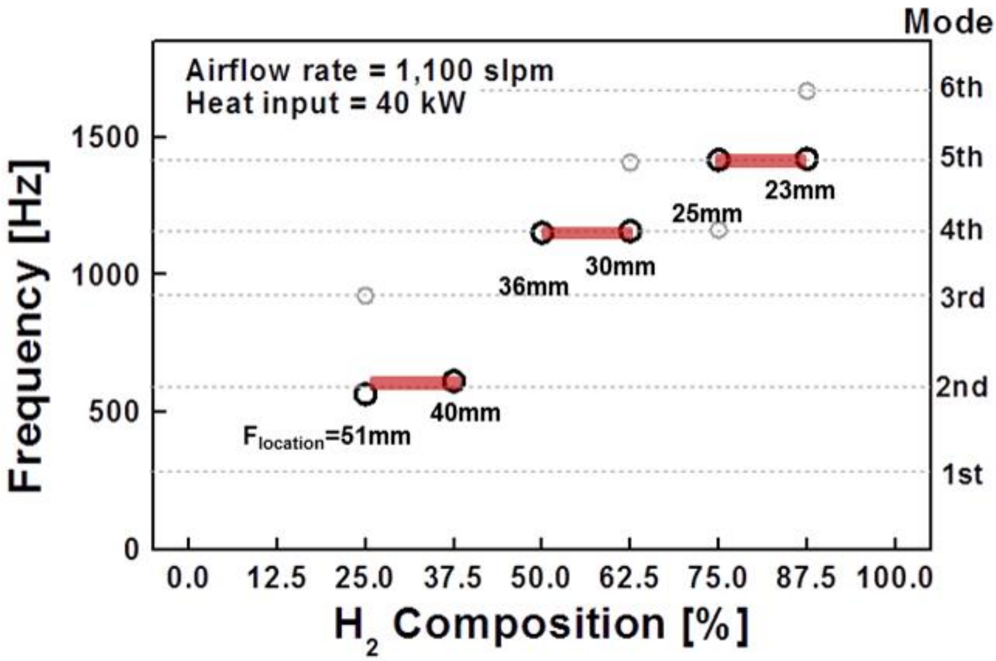

Figure 3.6 Prediction of instability mode shifting with fuel composition variation.

This predictions are consistent with the instability mode shifting phenomenon as shown in Figure 3.7, which was interpreted through unburned mixture length and convention time in the previous results of this research group. The measured FTF data and 1D lumped method confirmed that it is possible to roughly analyze and predict combustion instability characteristics. In the 1D lumped method, the combustion instability and the instability mode shifting phenomenon are effectively predicted. However, in the case of H_2 75% composition, the longitudinal instability of the 6th mode occurred in the experiment, but there was a difference in predicting the longitudinal instability of the 5th mode as the dominant instability. In addition, there were many errors in predicting the magnitude of combustion instability with varying lengths while keeping the fuel composition constant. Additional studies were conducted to improve the accuracy of combustion instability prediction.

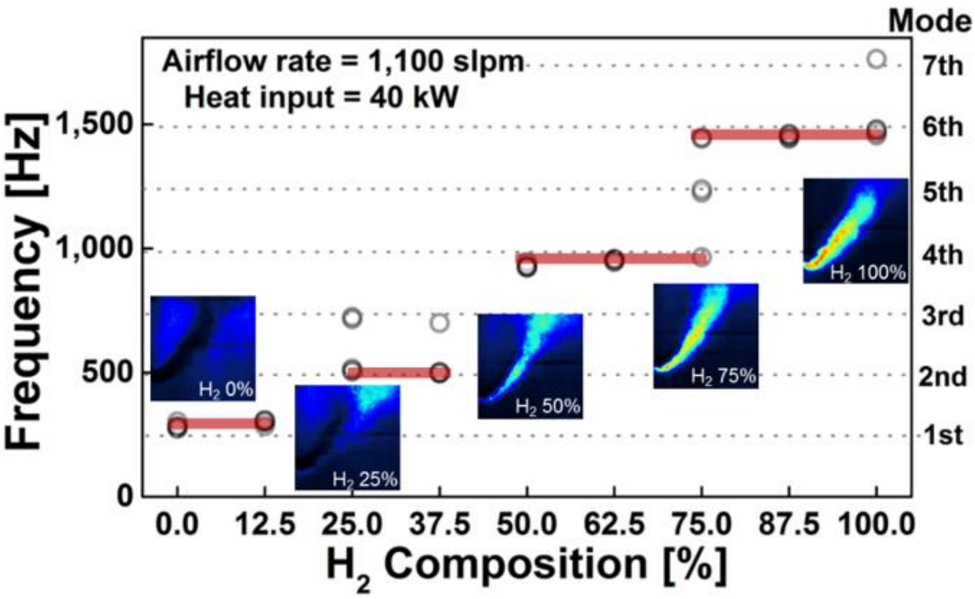

Figure 3.7 Experimental results of instability mode shifting with fuel composition variation (ref. [14]).

3.5 Prediction Accuracy Improvement

The instability mode shifting phenomenon in the partially premixed combustor in which the mechanism is described in the previous study, is predicted by the pre-measured FTF and the 1D lumped method. However, it was an incomplete approach because it did not consider the amplitude in combustion instability. It is necessary to judge whether the combustion instability is manifested as well as the instability frequency which is important in the prediction of combustion instability. However, unlike the well predicted frequency and mode congestion phenomena, the predicted growth rate did not agree well with the instability amplitude in combustion experiments.

In order to overcome these limitations, the temperature inside the combustor and the reflection coefficient were applied to the 1D lumped method. However, unlike the temperature data obtained for all the fuel compositions, the reflection coefficient was only obtained at the 25% H_2 fuel composition, so only this reflection coefficient was applied for improvement.

3.5.1 Application of Combustor Temperature

Previously, the adiabatic flame temperature was calculated by NASA's CEA code and used as a step function in the 1D lumped method. In order to improve the prediction accuracy, the temperature in combustion experiments were used instead of the adiabatic flame temperature. Because the predicted frequency is sensitive to the temperature at the point being measured, temperature data should be chosen that is as close to the average combustion temperature as possible. Unlike other thermocouples installed at the boundary of the combustor, the combustor temperature measured using an R type thermocouple (470 mm, based on the dump surface) inserted up to the center depth of the combustor was used as the representative temperature.

Figure 3.8 reveals only predicted dominant frequency of the longitudinal combustion instability compared with the experimental values by varying the length of the combustor. At first, since the adiabatic flame temperature was used, it was different from the instability frequency of experimental results even though the thermal properties were adjusted as much as possible using the NASA CEA code. To reduce the error of instability frequency, the temperature data measured by the R-type thermocouple was selected as input in the 1D lumped method.

The data shown in Figure 3.9 offers the prediction of instability frequency with increasing combustor length when the combustor temperature is applied. In combustion experiments, quartz installed for flame visualization is cooled by air and the plug nozzle and the combustor are cooled by water, so the average temperature is lower than the adiabatic flame temperature. Therefore, as a result of using the data that can represent the temperature of the combustor rather than the adiabatic flame temperature, the combustion instability frequency can be predicted almost in agreement with the experimental value. However, since the predicted growth rate is still inconsistent with the amplitude of the combustion instability, it is difficult to predict if combustion instability occurs under certain conditions.

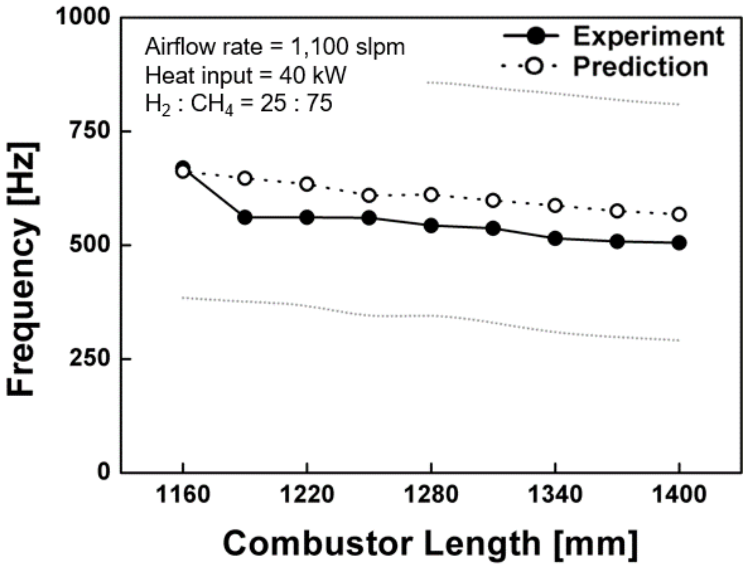

Figure 3.8 Instability frequency with combustor length when using adiabatic flame temperature.

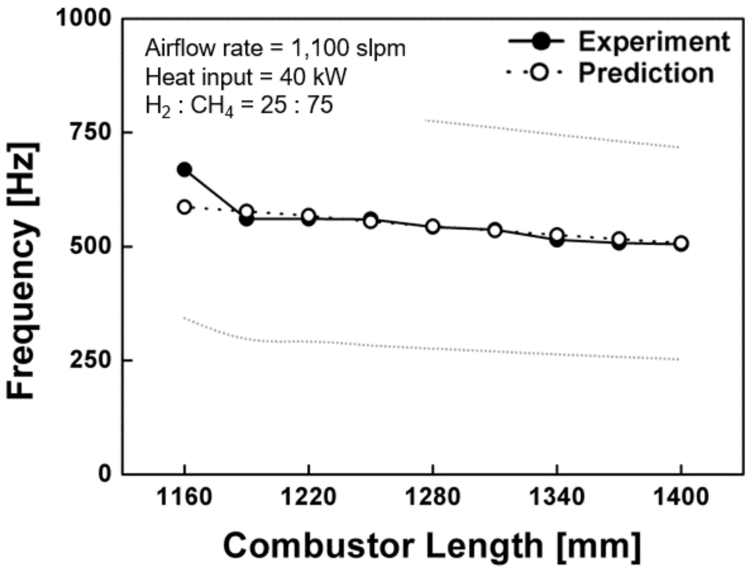

Figure 3.9 Instability frequency with combustor length when using combustor temperature.

3.5.2 Application of Reflection Coefficient

When the reflection coefficient of the inlet is adjusted, the combustion instability prediction result is different even when the same FTF and temperature data are applied. Therefore, it is possible to obtain more accurate prediction results by applying the reflection coefficient in combustion experiments. In the previous prediction, the gain of the reflection coefficient set at the inlet and outlet was set to 1 constantly, regardless of the frequency, as indicated by the dotted line in the Figure 3.10. Therefore, in order to apply a more realistic reflection coefficient, the gain of the reflection coefficient data was applied as a function by setting as shown by the solid line in the Figure 3.10 based on the measured reflection coefficient at the 25% H_2 fuel composition.

Phase of the reflection coefficient was also wanted to be input as data in real combustion experiment like gain. In the case of the conventional phase of reflection coefficient, the inlet boundary is set to 1 as an open boundary and the exit boundary is set to 0 as a closed boundary, as indicated by the dashed line in the Figure 3.11. In order to improve this, it was applied by setting the function as the solid line in the Figure 3.11 based on the measured phase data at 25% H_2 fuel composition.

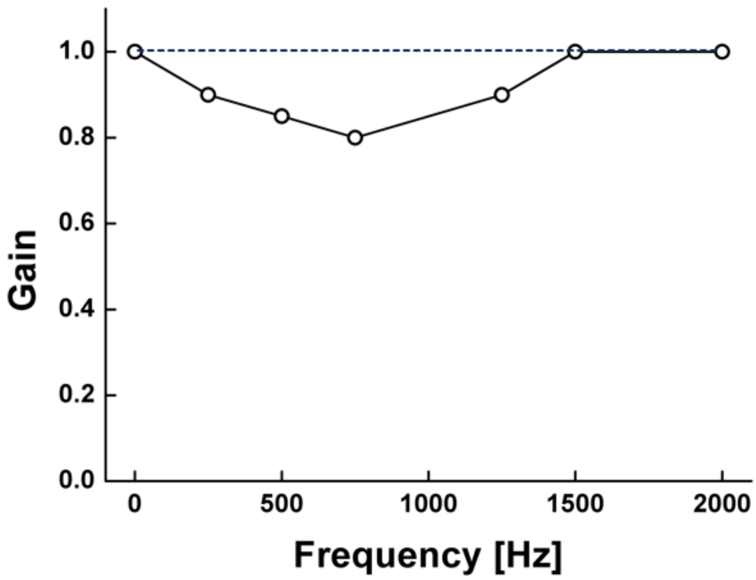

Figure 3.10 Gain of the reflection coefficient at 25% H_2 fuel composition.

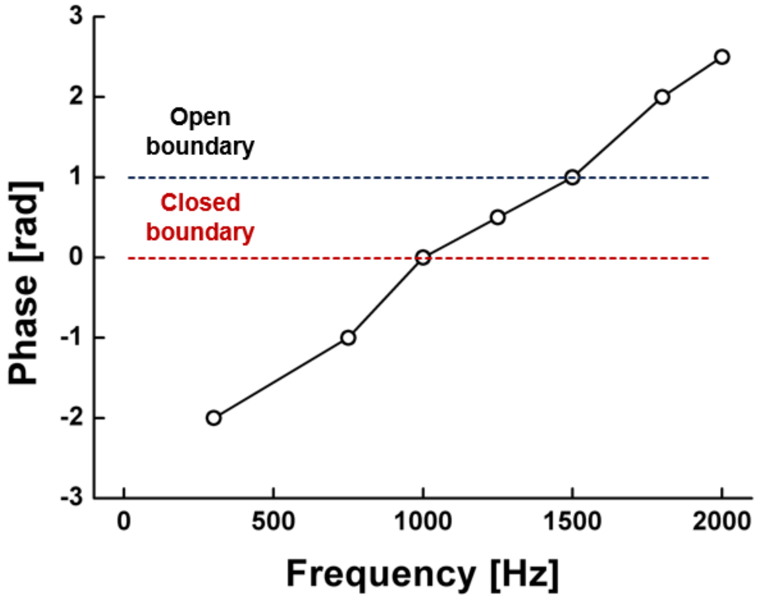

Figure 3.11 Phase of the reflection coefficient at 25% H_2 fuel composition.

Figure 3.5 shows the change in growth rate by frequency at the H_2 percentages of 25%, 50%, and 75%. It can be seen that, even before the improvement of accuracy, the dominant longitudinal instability mode shifting is predicted successfully as the percentages of H2 fuel composition increases. However, the data shown in Figure 3.5 offers that only 4^{th}, 5^{th} instability modes are predicted to occur, unlike the experimental results that show 4^{th}, 5^{th}, and 6^{th} instability mode for the 75% H_2 fuel composition.

Using the temperature of combustor instead of the adiabatic flame temperature helps improve the accuracy of the instability frequency prediction, but does not significantly affect the growth rate of the instability mode. Therefore, not only the temperature data but also the reflection coefficient data measured in the experiment were used. Figure 3.12 gives the growth rate of each instability frequency applied the temperature and the reflection coefficient. The improvement prediction results show that the growth rate for the 75% H_2 fuel composition was more than 0 at 4th, 5th, and 6^{th} mode. This corresponds exactly to the experimental results of combustion instability for the 75% H_2 fuel composition.

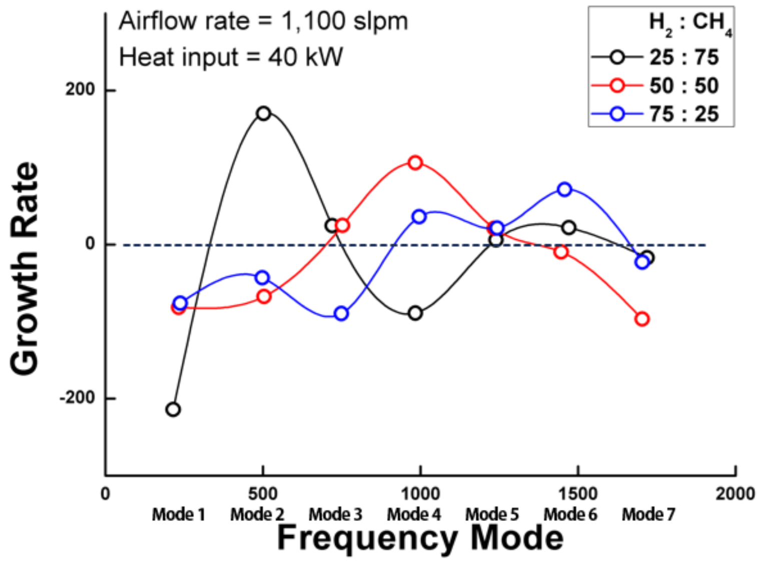

Figure 3.12 Improved prediction of growth rate for instability mode with fuel composition variation.

The prediction of the amplitude of the combustion instability was attempted using a more accurate reflection coefficient. In the graph on the Figure 3.13 before the reflection coefficient application, the black line offers that the growth rate obtained from the prediction is strongest at 1220 mm, and the size of the growth rate decreases as the length of the combustor increases. On the other hand, the results of the combustion test indicated by red line did not cause instability in the short combustor length, but rather instability in the long combustor length condition. In other words, it not only overestimates the instability prediction but also has a limitation that it can't keep up with the tendency of instability range due to combustor length change. Therefore, the transition of the growth rate according to the length of the combustor was analyzed by applying the reflection coefficient of 25% H_2 fuel composition to the boundary condition of the inlet.

As a result of improved prediction, as shown in Figure 3.14, although the growth rate is still overestimated, it is confirmed that trends of combustion instability are consistent. Prediction showed the instability amplitude peak under similar condition in the instability experiment and suggested a direction to avoid combustion unstable region. From the results, it can be seen that if the length of the combustor can be designed from 1160 mm to 1400 mm, shorter than 1370 mm can contribute to combustion stability. In addition, assuming that the combustion instability does not occur under the condition that the growth rate data is less than about 165, the black line is almost the same as the red line indicating the instability phenomenon of experiment. In other words, there is a possibility that not only the rough unstable region can be predicted but also the precise boundary of the combustion instability manifestation.

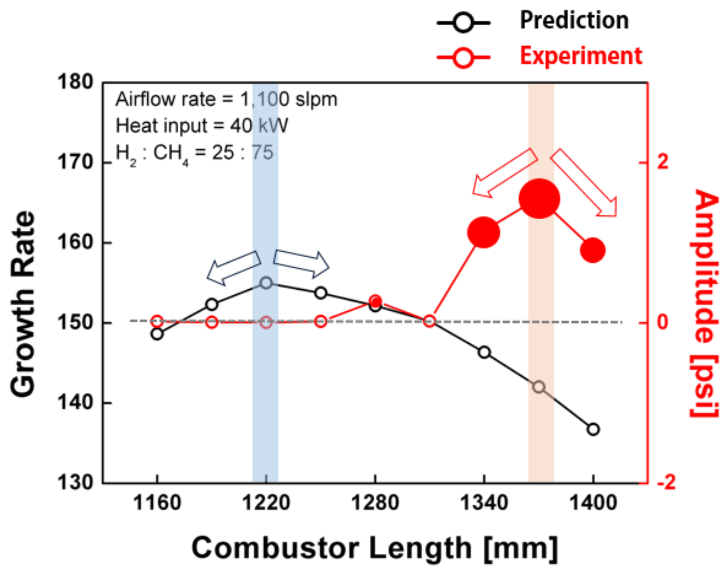

Figure 3.13 Growth rate with combustor length variation before reflection coefficient application.

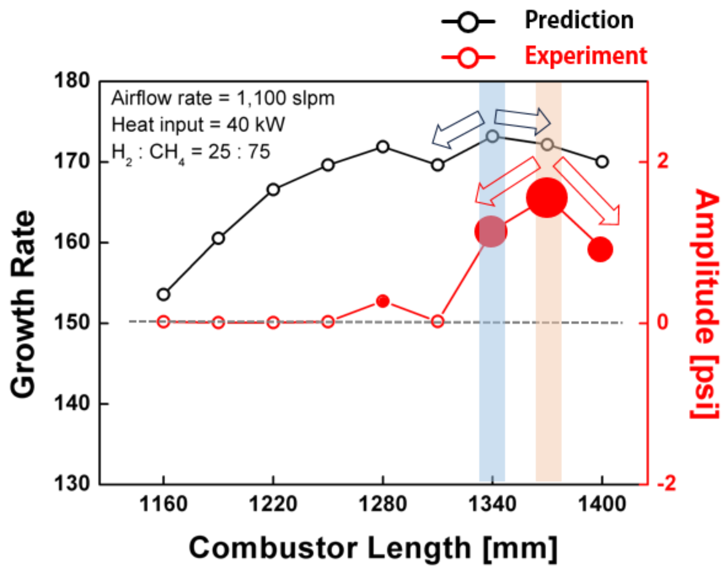

Figure 3.14 Growth rate with combustor length variation after reflection coefficient application.

CHAPTER 4

CONCLUSION

The computational studies were conducted to analyze and predict the characteristics of combustion instability in partially premixed model combustor using pre-measured FTF and 1D lumped method. The effect of combustor length, flame position, and fuel composition on the instability characteristic was investigated. It has also been attempted to improve the accuracy of the prediction using temperature and reflection coefficient.

It was confirmed that the predictions of instability frequency of longitudinal mode and coexistence of combustion instability mode are similar to those of experimental results. As the length of the combustor increases, a decrease in the combustion instability frequency and a change in the instability mode are predicted, which is consistent with the instability characteristics of the experiment. The study also suggests that there is a possibility of instability mode shifting by only changing the position of the flame, which is a major factor in the combustion instability of the partially premixed combustor.

In addition, combustion instability with H_2 fuel compositions variation was analyzed. As a result, prediction of combustion instability mode shifting phenomenon, which is distinctive characteristic of a partially premixed combustor, has been successfully achieved. Finally, improved prediction of instability frequency and tendency of instability amplitude are presented by applying combustor temperature and reflection coefficient of experiment.

Based on these results, if the FTF results of the nozzle can be obtained, the combustion instability characteristics can be sufficiently predicted for combustors in which the longitudinal mode is dominant. It is also expected to predict the instability tendency and suggest the direction to avoid instability during design and operation.

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초 록

최근 들어 봄철마다 빈발하는 고농도 미세먼지 사태는 동아시아 지역의 심각한 문제로 대두되고 있다. 친환경 발전 형태인 복합화력발전의 발전량을 늘려나가는 전략이 이러한 미세먼지 사태 해결에 큰 도움이 될 것으로 기대된다. Syngas, synthetic natural gas (SNG), biogas 등 다양한 조성의 연료를 사용할 수 있는 가스터빈은 미세먼지는 물론 배기 배출물 저감에도 효과적이기에 국내외적으로 꾸준히 개발되고 있다. 가스터빈에 사용되는 부분 예혼합 연소기는 기본적으로 희박연소로 설계되어, 연소불안정 현상이 발생할 가능성을 내포하고 있다. 그렇기에 가스터빈 연소기 개발에 있어, 다양한 연료조성에 대한 연소불안정 현상의 이해와 예측이 중요하다.

본 연구의 목적은 1D lumped method를 활용하여 부분 예혼합 연소기의 연소실 길이, 화염위치, 연료조성 변화에 따른 연소불안정 특성을 분석하고, 부분 예혼합 연소기의 특이한 현상이었던 불안정 모드 천이를 처음으로 예측하는데 있다. 먼저, Photomultiplier tube (PMT)와 Hot wire anemometry (HWA)를 사용하여 다양한 연료조성에서의 화염전달함수를 획득하였다. 이후 연소실 길이와 OH-PLIF 이미지로 획득한 화염의 위치를 변화시켰으며, NASA의 CEA 코드를 사용하여 계산된 다양한 연료조성의 열물성치가 적용되었다.

지배적인 종방향 불안정 주파수와 다중 불안정 모드에 대한 예측이 연소실험과 유사한 결과를 보여주었다. 연소실 길이가 증가함에 따라 연소불안정 주파수의 감소와 지배적인 불안정 모드의 천이가 예측되었다.

또한 화염위치에 따른 연소불안정 특성을 분석한 결과, 화염전달함수와 연료 및 공기 유량이 동일한 조건에서 화염위치 변화만으로도 불안정 모드 천이 현상이 예측됨을 확인하였다. 화염전달함수 계측이 가능하였던 모든 연료조성에서 수소의 비율이 증가함에 따라 불안정 모드가 증가하는 모드 천이 현상이 실험에서와 같이 예측되었다. 추가연구로 연소실의 온도와 반사계수를 적용하여 불안정 주파수와 진폭 경향성 예측의 정확도를 향상시켰다. 이러한 연구 결과를 바탕으로 연소실 설계나 운용 단계에서 연소불안정 발현 여부와 불안정 조건 회피 방향을 제시할 수 있을 것으로 생각된다.

주요어: 연소불안정, 1D lumped method, 화염전달함수, 부분 예혼합 연소기, 연소불안정 예측, 불안정 모드 천이 현상, 다중 불안정 모드

학 번: 2013-20658