Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 99 (2015) 304 – 312

Procedia Engineering

www.elsevier.com/locate/procedia

"APISAT2014", 2014 Asia-Pacific International Symposium on Aerospace Technology, APISAT2014

Experimental Study on Spectral Characteristics of Kerosene Swirl Combustion

Hyeonjae Lee, Seonghyeon Seo*

Department of Mechanical Engineering, Hanbat National University, Daejeon 305-719, South Korea

Abstract

An experimental study has been conducted to investigate characteristics of emission spectra from combustion of kerosene liquid fuel, i.e., jet A-1. Radicals of interest in hydrocarbon combustion are OH*, CH*, and C_2*. An experimental study about chemiluminescence characteristics of liquid fuel combustion has been devised to investigate emission characteristics depending on various operating parameters. A swirl combustor is designed for providing similar environments to those of actual liquid rocket engines. The model combustor has a central fuel injector making a hollow cone spray, which is surrounded by swirling flow. Kerosene flame exhibited highly luminous characteristics being attributed to CO_2* chemiluminescence. OH* and CH* chemiluminescence intensities show a very similar trend as a function of equivalence ratio. And their intensities decrease along with an increase in equivalence ratio. The chemiluminescence intensity ratios between these two radicals show very close values to one regardless of equivalence ratio. C_2* chemiluminescence intensity reveals relatively strong relations with equivalence ratio compared to CH* and OH*. Its intensity values increase as mixture becomes rich and also an increase in inlet air temperature enhances its intensities. The ratios between C_2* and CH* manifest a linear relation as a function of equivalence ratio.

Peer-review under responsibility of Chinese Society of Aeronautics and Astronautics (CSAA)

Keywords: Kerosene Combustion; Chemiluminescsence; Emission Spectra; Swirl; Heat Release Rate; Liquid Fuel

* Corresponding author. Tel.: +82-42-821-1078; fax: +82-42-821-1587.
E-mail address: shseo@hanbat.ac.kr

Peer-review under responsibility of Chinese Society of Aeronautics and Astronautics (CSAA)
doi:10.1016/j.proeng.2014.12.539

1. Introduction

Combustion devices for modern power and propulsion systems operate at excessively high pressure. For example, gas turbine combustors are required to run at higher turbine inlet temperature for the purpose of increase in a thermal efficiency along with the prevention of environmental pollution[1,2]. Thus, techniques for the accurate diagnosis of the flame are required for the high-performance and efficient combustion system of the stable operation for long hours[3]. A need of the monitoring method of the flame condition is increasing for various combustion systems. A technique for accurately monitoring flame behavior is necessary for the application of the active control when need observing combustion instability phenomena[4,5]. For example, the equivalence ratio control is essential for the reduction of the environmental pollution at the ground generated gas-turbine combustion using lean premixed flame. The measurement technology to understand the dynamic characteristics of the flame for the control of the high frequency combustion instability is needed at the high energy density combustion environment.

There are the active and the passive measurement methods for understanding of physical characteristics of combustion. The active method grasps physical characteristics of the flame using the artificial and the outside energy. The passive method makes efforts for understanding of physical characteristics of emitted energy from combustion.

A number of studies on spontaneous emission of flame, chemiluminescence, are much reported because a measurement method of chemiluminescence of flame can easily analyze the physical characteristic without direct effect. The study for measuring the intensities of released chemiluminescence has also been frequently conducted in order to utilize the equivalence ratio and heat release rate measurement signal by using the various radical such as CH*, OH*, C_2*, and CO_2*.

The study for equivalence ratio to take advantage of chemiluminescence signal has been conducted to be applied to gas turbine combustion using natural gas for reduction of nitric oxides at lean premixed operating conditions. For such reasons, the research was mainly conducted on premixed methane flame. Docquier *et al.*[6] observed characteristic changes of chemiluminescence (OH*, CH* and C_2*) according to combustion pressure(1-10 bar) and equivalence ratio(0.6-1.1). Each radical of chemiluminescence characteristics shows separate tendencies. Chemical signals with the occurrence of radicals are closely related with pressure. OH* radical indicated a suitable indicator in lean conditions, and CH* and C_2* radicals show appropriate indicators in rich conditions. Therefore, authors suggested the use of two or three radical signals for the inclusion of the whole equivalence ratios, and concluded that OH* signal is relatively smaller than the signal changes of CH* and C_2* according to pressure. Kojima *et al.*[7] measured the chemiluminescence intensity of OH*, CH* and C_2* in order to improve the spatial resolution and remove the chromatic aberration with the application of Cassegrain optics[8] at two-dimensional laminar methane/air flame. As a result, OH*/CH* signal values showed high correlations with equivalence ratios below 1.35. Nori and Seitzamn[9] reported that CH*/ OH* signal intensity was effective in measuring equivalence ratio on limited pressure and temperature conditions at lean methane combustion. Orain and Hardalupas[10] measured the chemiluminescence of OH*, CH*, and C_2* by using various fuels such as propane, isooctane, ethanol, and methanol at a premixed counter flow burner. As measurement results of the chemiluminescence intensity, the indicator of heat release rate from flame was closely related with a fuel type. In cases of propane and isooctane, the intensity of OH*/CH* decreased with an increase in equivalence ratio.

In case of measuring heat release rate, chemiluminescence of hydrocarbon fuel including OH* and CH* signal intensities has been considered as a qualitative and indirect value. For such a reason, OH* and CH* imaging or signal measuring technique is widely used to assess heat release rate. Hardalupas and Orain[11] carried out recognition of relationship between heat release rate and OH*, CH*, and C_2* chemiluminescence with changes in strain rate and gas exit velocity at a premixed counter flow burner. OH*, CH* and CO_2* chemiluminescence signals were good indicators except C_2*. Nori and Seitzaman[9] reported that the relations between CH* chemiluminescence and heat release rate are affected by equivalence ratio, pressure, temperature and strain rate at high pressure conditions. CH* intensity can be utilized as a measurement signal of heat release rate at high pressure combustion. Also an increase in temperature of reactants reduced the influence of flame strain on chemiluminescence signal.

The main objective of the present study is to experimentally investigate spectral emissions characteristics of swirl combustion burning liquid hydrocarbon, i.e., Jet A-1. Spectral characteristics of liquid fuel combustion will be analysed and presented along with changes in various operating parameters of model combustors. Effects of parameters like equivalence ratio, swirl strength, and inlet air temperature are systematically investigated and thus, their preliminary results are discussed here in this paper. Signal analysis methods are introduced for using chemiluminescence intensities as a good indicator for heat release rate from combustion. Results of the present study are expected to provide valuable information on chemiluminescence characteristics related with combustion physical properties like heat release rate, which will be used for designing an optical sensor that measures temporal variations of heat release rate of flame inside of a combustion chamber.

2. Chemiluminescence

Light emissions from combustion contain valuable information on its physics. Among them, chemiluminescence is related to species formation and physical properties in combustion since it is generated from the transition of thermally excited radical from a high energy state down to a low state. Radicals of interest in hydrocarbon combustion are OH*, CH*, and C_2*. Their outstanding emission wavelengths for OH*, CH*, and C_2* are 306-315, 431, and 516.5 nm, respectively. These molecules as changing energy phase difference of spontaneous emission have particular wavelength in each kind of gas elements in ultraviolet and visible light and this phenomenon refers to chemiluminescence. Chemiluminescence of molecules in each wavelength is listed in the Table 1.

Research on the measurement and analysis of chemiluminescence are intensively conducted due to its relatively easy-to-measure characteristics compared to laser-based diagnostic techniques. From this reason, a relation between intensity of chemiluminescence and an equivalence ratio of combustion has been heavily studied.

3. Experimental setup

Figure 1 is the model combustor. For the acquisition spontaneous emission of flame, experiments were conducted in the swirl combustor to simulate liquid rocket engines. In order that swirl flame is formation of strong flame, swirl vanes with tangential entries in the combustor induce swirl on incoming air flow. Swirl vanes are three types and swirl numbers include 0.60, 0.84, and 1.30. Swirl number is introduced like the results of Sheen *et al*[13].

The swirl combustor simulates combustion environment of liquid rocket engine, strong flame enhances the flame stability. A modification in swirl strength was achieved by changing the vane angle. Swirl vane angles are 40, 45 and 50 degrees. Its strength in terms of swirl number was estimated to be 0.60, 0.84 and 1.30. Swirl strength has an effect on inner air and mixing degree of fuel and air.

Air is injected at the tangential direction after preheated. Inlet air temperature ranged from 350 to 500K, and air pressure supplied at 5 bar. Air was supplied by the oil-free compressor and a flow rate was controlled by a MFC(mass flow controller, TSC 145) with a range of 0 to 10 g/s with 2% uncertainty. Fuel is injected through the central spray with a hollow cone of 80-degree spray angles. Liquid fuel, Jet A-1, was stored in a pressurized tank. A fuel flow rate was controlled by a TFM(turbine flow meter, McMillan 104) in a range of 0 to 2.0 g/s with 1% uncertainty.

Table 1. Excited Radicals and Their Emissions[12].

Radical	Transition	Wavelength (nm)
CH*	$B^2\Sigma^- \rightarrow X^2\Pi$	387.1
CH*	$A^2\Delta \rightarrow X^2\Pi$	431.4
OH*	$A^2\Sigma^+ \rightarrow X^2\Pi(\Delta\nu = 1)$	282.9
OH*	$A^2\Sigma^+ \rightarrow X^2\Pi(\Delta\nu = 0)$	308.9
C_2*	$A^3\Sigma_3 \rightarrow X^2\Pi_u$	516.5
CO_2*	Continuum	305~500

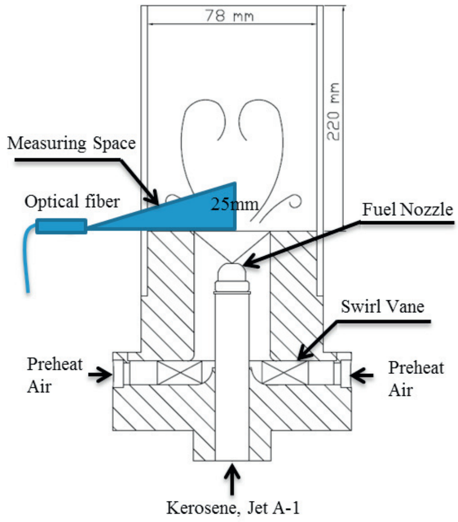

Fig. 1. Cross sectional view of the combustor.

For measuring the spectrum, A spectrometer(Ocean Optics corp., USB-2000+) was used. The spectrometer was employed with an optical fiber. Flame spectra were acquired at the flame upstream with an exposure time of 200 msec and an average of 100 shots. Electronic signals of each sensor were measured from data acquisition system(NI cDAQ-9178) and spectrum signals are processed using Spectra Suite of Ocean Optics corp., a commercial program. Direct images of the flame were captured using a digital camera(Nikon, D40).

4. Result

This section presents experimental results including photographic flame structures, measurements of chemiluminescence intensities from OH*, CH* and C_2*, and corresponding ratios of intensities in kerosene swirl partially premixed flame, operating at an equivalence ratio range of 0.6 to 1.3. The measurements of intensity were obtained at the partial section of the flame. Since kerosene liquid fuel flame has a very strong luminosity, initial experimental results measuring whole flame area, cannot reveal out OH*, CH* and C_2* intensities. Measuring area corresponds to the half circle with a diameter of 25 mm having the centerline aligned to the dump plane of the combustor. All spectra were acquired at an exposure time of 200 msec and an average of 100 shots.

4.1. Chemiluminescence spectra

Typical spectra of kerosene flame are shown in Fig. 2 for different equivalence ratios at an air inlet temperature of 400 K. As mentioned before, flame spectra are acquired with the optical fiber and the spectrometer for different swirl strengths and equivalence ratios. All spectrum data were deducted from the dark spectrum value in the laboratory. Baseline spectrum without flame was measured before each experiment.

CO_2* chemiluminescence with a broadband grows strong with an increase of equivalence ratio. The flame spectra of Fig. 2 shows a peak of intensity at wavelengths relevant to chemiluminescence from the OH* radicals between 305.65 to 321.5 nm, CH* radicals between 421.72 to 433.52 nm, and C_2* radials between 512.46 to 517.67 nm. The chemiluminescence intensities from each radical were estimated by the summation of intensity values falling between the selected values of the lower and the upper wavelengths.

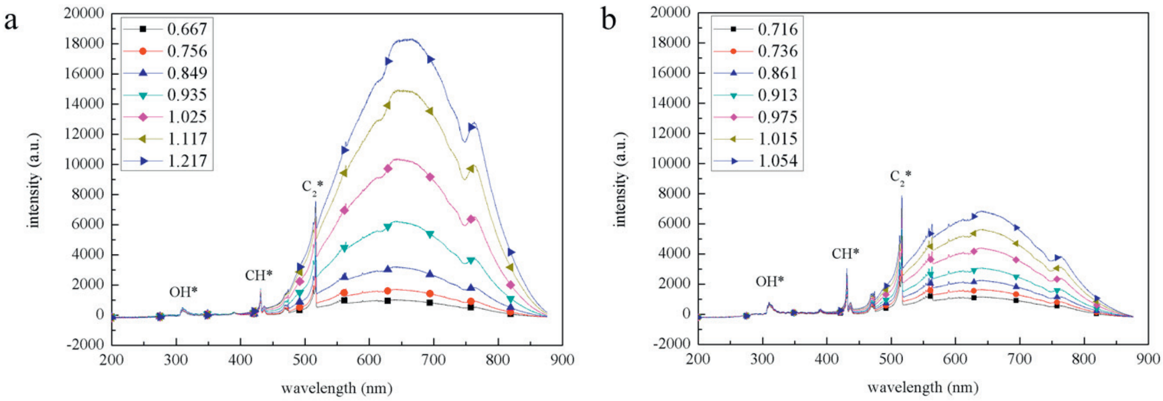

Fig. 2. Typical emission spectra for different equivalence ratios at an air inlet temperature of 400 K with a swirl number of 1.30 along with; (a) the variations in air mass flow rate, (b) the variations in fuel mass flow rate.

The graphs in Fig. 2(a) and 2(b) present the emission spectra with the variations in air mass flow rate and the variations in fuel mass flow rate, respectively. Fig. 2(a) shows a rapid increase in overall luminosity along with an increase in equivalence ratio. On the other hand, Fig. 2(b) indicated the gradual increase of overall intensities. Direct comparison shows that intensity variations of flame spectra are relatively stable with the variations in fuel mass flow rate. In addition, blue flame was strong, and OH*, CH*, and C_2* radicals strongly occurred in case of the change of fuel mass flow rate, which indicates that fuel and air mixes relatively better with an increase in air flow velocity.

4.2. Chemiluminescence intensity

The above result indicates a common behavior of the swirl strength for the swirl number of 0.60, 0.84 and 1.30. Figures 3 to 5 show the integrated intensity results and present chemiluminescence intensity integration ratios between three species, i.e., C_2*/CH* and OH*/CH* for a number of equivalence ratios. OH* chemiluminescence intensity indicates the integrated value for a range of 305.65-321.5 nm. CH* chemiluminescence intensity presents for a range of 421.72-433.52 nm. The last one of C_2* chemiluminescence intensity shows a range of 512.46-517.67 nm.

Figure 3 show the intensities at both swirl numbers of 0.60 and 0.84 for three different inlet air temperatures. In Fig. 3(a), 3(b) and 3(c), OH* and CH* intensities of peak occurred from equivalence ratio range of 0.7 – 0.8. Since then, OH* and CH* intensities indicated a gradual decrease. C_2* intensities shows a gradual increase. In Fig. 3(d), 3(e), and 3(f), a similar trend can be identified like as Fig. 3(a-c) in overall. Figure 3(f) shows the different tendency. Flame at an air inlet temperature of 500 K revealed different characteristics.

In this case, OH* and CH* intensities represented to the decreasing intensity from equivalence ratio of 1.0 and peak intensities occurred from equivalence ratio of 1.1. C_2* intensities declined from equivalence ratio range of 0.8 – 0.9 after the increase. As mentioned, the unstable flame have great effect on formation of C_2* intensity but OH* and CH* intensity were scarcely affected by unstable flame. Figure 3(d-f) for a swirl number of 0.84 shows a similar trend like as the swirl number of 0.6 except unstable flame condition state. In the other hands, C_2* reveals a linear response and strongly emits as a mixture goes to fuel rich conditions.

Figure 4 shows the intensities at a swirl number of 1.30. In Fig. 4(a), OH* and CH* intensities indicated nearly constant below equivalence ratio of 1.0 since than its intensities decrease. Also C_2* intensities gradually increase. Peak intensities occurred from equivalence ratio of 1.1. In case of Fig. 4(b), OH* and CH* intensities in equivalence ratio section of 0.9 show the decrease tendency. Also C_2* intensities steadily increased, peak intensities showed at equivalence ratio of 1.2. Therefore, Fig. 4(b) can identify the similar tendency like as Fig. 4(a).

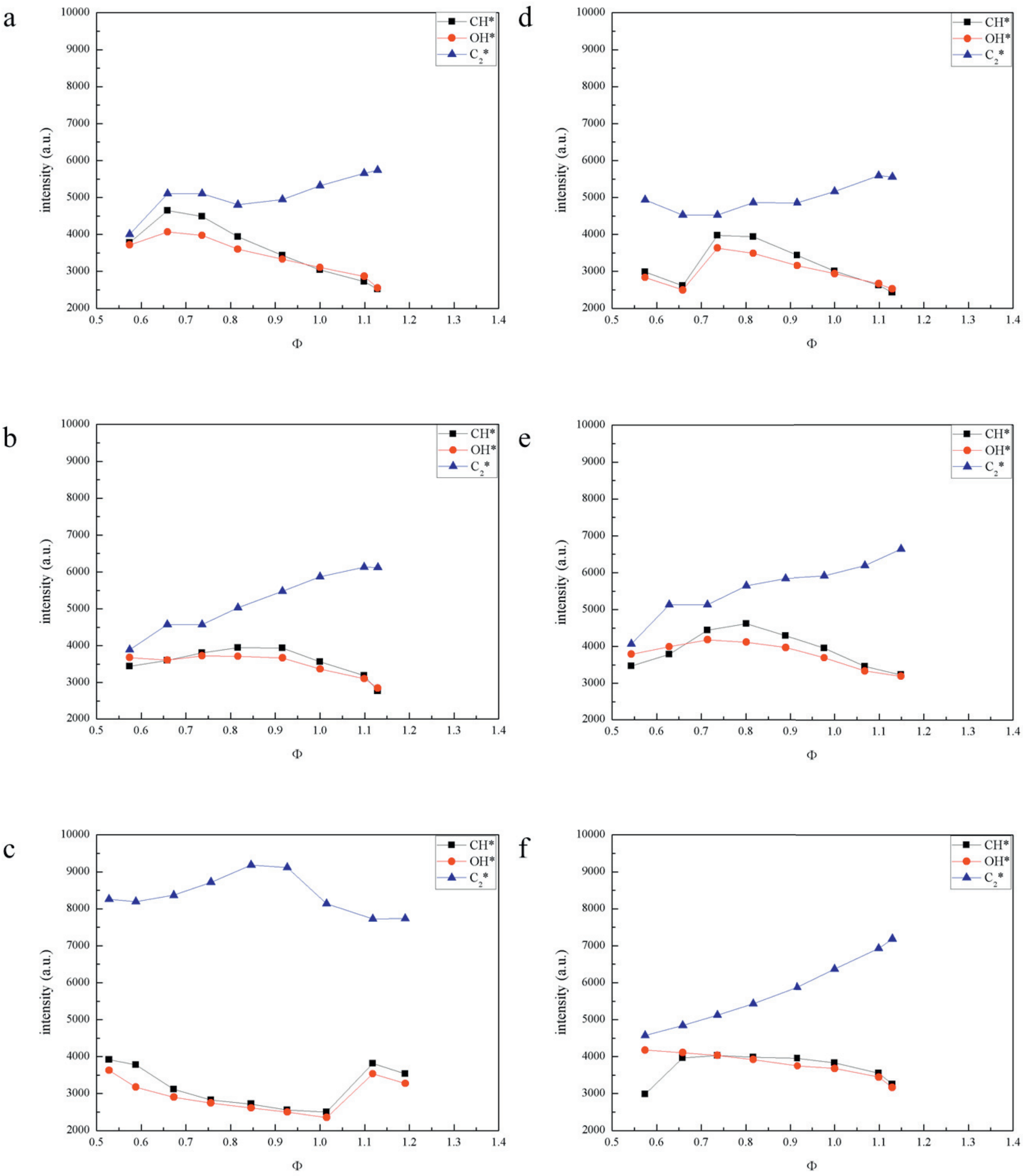

Fig. 3. Integrated intensities of CH*, OH*, C_2* at a swirl number of 0.60 with an air inlet temperature of; (a) 400 K, (b) 450 K, (c) 500 K, and swirl number of 0.84 with an air inlet temperature of; (d) 400K, (e) 450 K, (f) 500 K.

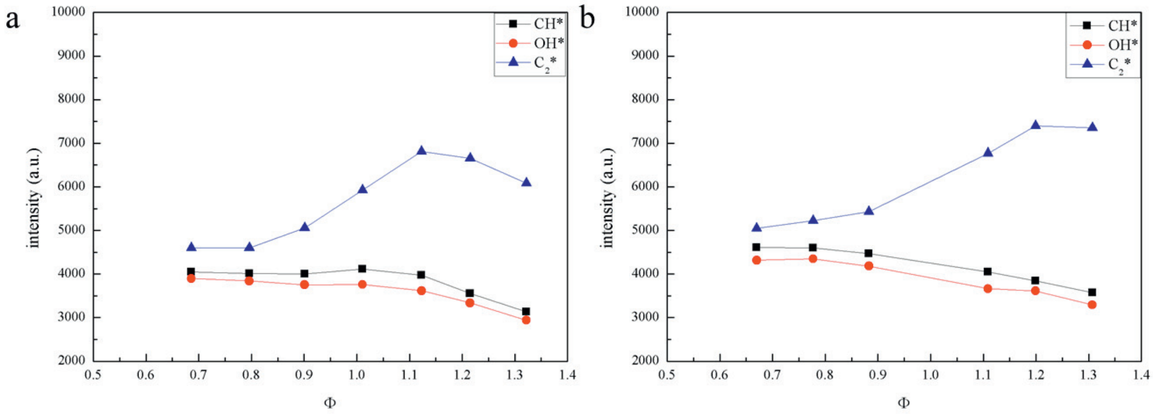

Fig. 4. Integrated intensities of CH*, OH*, C_2* at a swirl number of 1.30 with an air inlet temperature of; (a) 400 K, (b) 450 K.

In overall, all results represent a similar form. The increase of swirl number improved OH* and CH* intensities over equivalence ratio. Since mixing degree is affected by swirl number, flame is stable. Thus CH* and OH* intensity are increased from equivalence ratio of 0.8 – 1.2.

Figure 5 presents chemiluminescence intensity ratios between three species, C_2*/CH* and OH*/CH*. Fig. 5(a) is intensity ratio at an inlet air temperature of 400 K. OH*/CH* intensity ratio show the constant form on swirl number of 1.30. In the other hand, swirl number of 0.60 and 0.84 indicated the gradually increase after equivalence ratio of 0.8. In generally, flame condition and mixing degree of fuel/air show stable state. In Fig. 5(b), intensity ratio maintained a constant value at all swirl number. Thus, increase temperature improved stability of flame according to boosted vaporization of fuel. Also measurements went smoothly. Fig. 5(c) shows the similar tendency except equivalence ratio range from 0.5 – 0.7. Because different characteristics of flame were measured on swirl number of 0.60. Different characteristics of flame indicated striking decrease of CH* intensities.

Figure 5(d-f) show the C_2*/CH* intensity ratio. Fig. 5(d) presented a constant rise except an equivalence ratio range of 0.5 – 0.7 at swirl number of 0.84. In case of swirl number of 1.30, intensities were the lowest, because the mixing degree is affected by C_2* intensity. Fig. 5(e) is for an inlet air temperature of 450 K., intensity ratio increase on equivalence ratio like as Fig. 5(d). Also, fuel of vaporization was improved by preheated air in swirl number of 0.60 and 0.84, therefore flame was stable according to improvement of mixing degree because the graph shows a similar tendency like those for a swirl number of 1.30. Fig. 5(f) shows intensity ratios at an inlet air temperature of 500 K. As mentioned, C_2*/CH* ratio do not measure at air swirl number of 1.30. In case of swirl number of 0.60, C_2*/CH* ratio brought about these results on increase of C_2* intensity. As mentioned, the case of swirl number of 0.84 show the increase tendency on equivalence ratio, the graph indicated gradually characteristics by reduced C_2* intensities.

Overall OH*/CH* ratio results show relatively similar trends regardless of swirl strength for varied equivalence ratio. In the other hand, C_2*/CH* results indicate the increasing tendency with an increase in equivalence ratio, also inlet air temperature has effects on the OH* and CH* intensities. However, ratios between intensities of two radicals are very close to one since their values are similar as shown in Fig. 4.

Even though OH*/CH* shows constant values with respect to an overall equivalence ratio, C_2*/CH* reveals a roughly linear response of the chemiluminescence ratios along with overall equivalence ratios except unstable flame state. Fig. 5(f) presents C_2*/CH* of the unstable flame state at an equivalence ratio of 0.9 at a swirl number of 0.6. It should be noted that the scale of the vertical axis is greater than others.

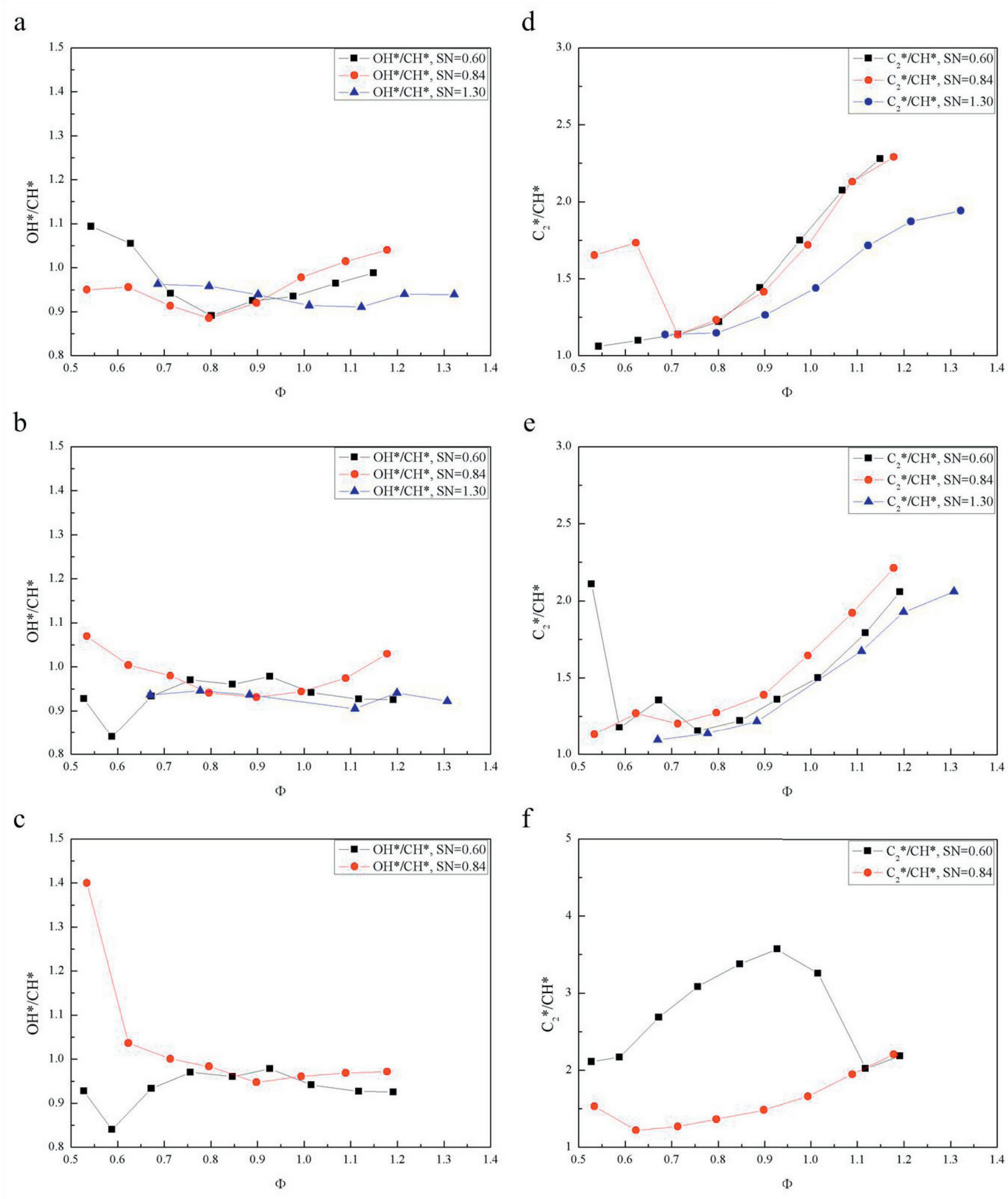

Fig. 5. Chemiluminescence intensity ratios of OH*/CH* at an air inlet temperature of; (a) 400 K, (b) 450 K, (c) 500 K and C_2*/CH* at an air inlet temperature of; (d) 400 K, (e) 450 K, (f) 500 K.

5. Conclusion

Here in this study, a model combustor burning a liquid fuel is employed for providing combustion environments simulating those in a liquid rocket thrust chamber. Emission spectra from flame were obtained at wide varieties of operating conditions including inlet air temperature, swirl strength and equivalence ratio. Fuel, i.e., Jet A-1, was partially premixed with incoming preheated air to simulate working conditions of practical liquid-fueled combustors. As expected, kerosene flame exhibited highly luminous characteristics being attributed to CO_2* chemiluminescence. The following can be concluded from the present study.

- OH* and CH* have a very similar trend and intensity value as a function of equivalence ratio. And their intensities decrease along with an increase in equivalence ratio. Overall intensity values increase with an increase of inlet air temperature due to enhanced reaction rates producing the radicals. The chemiluminescence intensity ratios between these two radicals show very close values to one regardless of equivalence ratio and inlet air temperature.
- C_2* chemiluminescence intensity reveals relatively strong relations with equivalence ratio compared to CH* and OH*. Its intensity values increase as mixture becomes rich and also an increase in inlet air temperature enhances its intensities. The ratios between C_2* and CH* manifest a linear relation as a function of equivalence ratio. Enhanced degree of mixing expected from stronger swirl results in a decrease of gradients of C_2* and CH* intensity ratio.

Future research plan includes acquisition of experimental data associated with the variations of fuel mass flow rate at a fixed air mass flow rate to investigate emission characteristics at different heat release rate from flame. This might allow us to better understand emission characteristics of kerosene flame and its applicability for practical use.

Acknowledgements

The present study is financially supported by the National Research Foundation of Korea grant funded by the Korean government Ministry of Education (MOE) (No. 2013R1A1A2005304) and the project titled “Research on the Core Technologies for Upper Stage Rocket Engines,” also funded by the Korean government Ministry of Science, ICT and Future Planning (MSIP).

References

[1] S.M. Correa, Twenty-Seventh Symposium (International) on Combustion, (1998) 1793–1807
[2] J.J. Smith, G. Schneider, D. Suslov, M. Oschwald, O. Haidn, Aerospace Science and Technology, 11 (2007) 39–47
[3] J. Ballester, T. García-Armingol, Progress in Energy and Combustion Science, 36 (2010) 375–411
[4] J.B. Swell, P.A. Sobieski, in Combustion Instabilities in Gas Turbine Engines: Operational Experience, Fundamental Mechanisms, and Modeling, (Eds.), T.C. Lieuwen, V. Yang, Progress in Astronautics and Aeronautics, 210 (2005) 147–162
[5] C.J. Goy, S.R. James, S. Rea, in Combustion Instabilities in Gas Turbine Engines: Operational Experience, Fundamental Mechanisms, and Modeling, (Eds.), T.C. Lieuwen, V. Yang, Progress in Astronautics and Aeronautics, 210 (2005) 163–175
[6] N. Docquier, S. Belhalfaoui, F. Lacas, N. Darabiha, C. Rolon, Proceedings of the Combustion Institute, 28 (2000) 1765–1774
[7] J. Kojima, Y. Ikeda, T. Nakajima, Combustion and Flame, 140 (2005) 34–45
[8] F. Akamatsu, T. Wakabayashi, S. Tsushima, M. Katsuki, Y. Mizutani, Y. Ikeda, N. Kawahara, T. Nakajima, Measurement Science and Technology, 10 (1999) 1240–1246
[9] V.N. Nori, J.M. Seitzman, 32 (2009) 895–903
[10] M. Orain, Y. Hardalupas, Comptes Rendus Mecanique, 338 (2010) 241–254
[11] Y. Hardalupas, M. Orain, Combustion and Flame, 139 (2004) 188–207
[12] N. Docquier, S. Candel, Progress in Energy and Combustion Science, 28 (2002) 107–150
[13] H.J. Sheen, W.J. Chen, S.Y. Jeng, Experimental Thermal and Fluid Science, 12 (1996) 444–451