$OH/CH/C_2$ Chemiluminescence of N_2 diluted CH_4 Edge Flames under Small Fuel Concentration Gradients

Jungkeuk Park[a], Minjung Lee[b], and Nam Il Kim[a]
[a] Korea Electric Power Corporation Research Institute
Daejeon, Republic of Korea
[b] Seoul National University of Science and Technology
Seoul, Republic of Korea
[c] Korea Advanced Institute of Science and Technology
Daejeon, Republic of Korea

Abstracts

Flame structures and chemiluminescence characteristics of N_2 diluted edge flames with fuel concentration gradient were experimentally investigated in a diverging narrow channel. It was found that sufficiently small fuel concentration gradients could distinguish three flame branches of an edge flame, i.e., a lean premixed flame branch, a rich premixed flame branch, and a diffusion flame branch downstream of the two premixed branches. OH, CH, and C_2 chemiluminescence were compared between two flames, i.e., premixed flame branches of edge flames under small fuel concentration gradients and well premixed Bunsen shape flames. Some trends were found between the edge flames and the Bunsen shape ones in the relative chemiluminescence. The chemiluminescence ratios of the Bunsen flames by other researchers showed monotonic variation against the equivalence ratio. However, in this study, Bunsen flames and edge flames had similar monotonic trends in most equivalence ratios but different non-monotonic trends near the flammability limits, and they were clearer for the edge flames. It can be explained by the reduced flammability due to N_2 dilution for all flames and the extended edge flame's flammability due to the help of neighboring flame branches. Consequently, edge flames could produce overall characteristics of major chemiluminescence much more efficiently, and this data can be used to assess flame structures.

1 Introduction

Less emission of greenhouse gases and particulate matters is getting more important in the energy and mobility industries. Especially thermal power plants are strongly requested to adopt clean combustion technologies, for which monitoring and optimizing technologies are getting more important. Chemiluminescence information of flames has been studied as a tool monitoring the equivalence ratio (ϕ) and the heat release rate [1-3]. Therefore, constructing a sufficient database of various chemiluminescence characteristics is an essential step for the monitoring method, and an efficient way to obtain chemiluminescence information for various conditions is demanded. An edge flame structure could be one solution since it contains three distinctive flame branches, i.e., a lean premixed, a rich premixed, and a non-premixed flame. Therefore, this study investigated the structure and chemiluminescence of a CH_4 edge flame experimentally in a diverging narrow channel, in which small fuel concentration gradients were introduced. After that, the results were analyzed and compared with those of well premixed Bunsen shape flames.

2 Experimental Setup and method

CH_4 edge flames were formed in a narrow diverging channel. Its inlet width was 30 mm, the diverging angle was 4°, and the gap was 8 mm, as shown in Fig. 1a. Mixtures of fuel, air, and N_2 were supplied from two inlets at the bottom. A mixing layer having a specific fuel concentration gradient (FCG) was formed in the channel by introducing a slightly larger fuel concentration in the right inlet ($\Delta Y_F = Y_{F,right} - Y_{F,left}$). Nitrogen dilution ratio (DR) was defined as the ratio of the volume flow rate of N_2 in the mixture of CH_4+N_2. Color images and chemiluminescence information of OH, CH, and C_2 radicals were obtained with four commercialized CCD cameras (1392×1040 pixels) equipped with proper band path filters. The intensities of three radicals, I_{OH}, I_{CH}, and I_{C_2} were normalized with the maximum intensities, respectively.
An additional burner configuration was used to acquire well-premixed flames like the Bunsen flames in the same burner structure, as shown in Fig. 1b. Two nozzle wedges were installed within the channel.

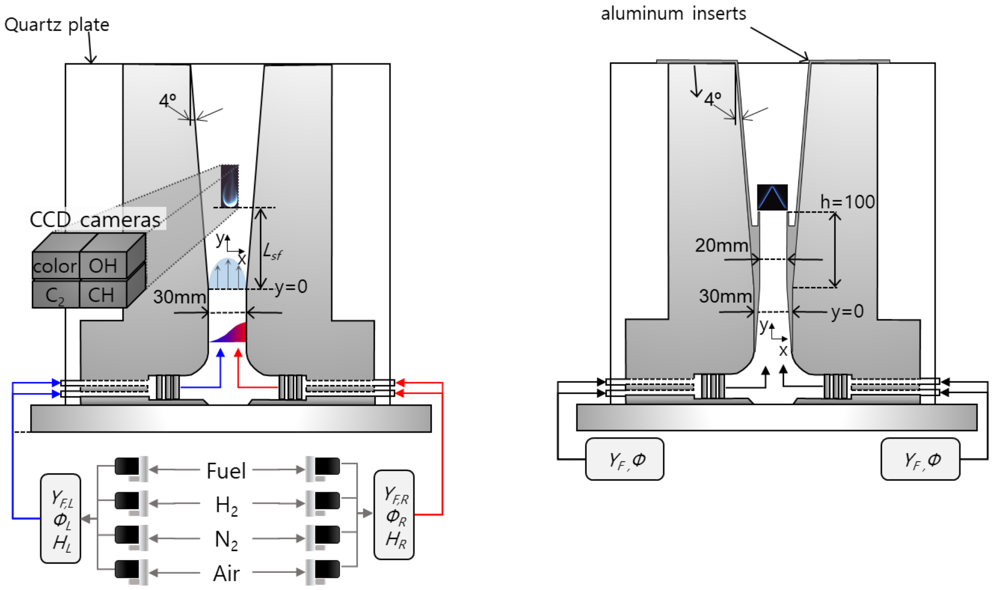

Figure 1: A narrow diverging mixing layer burner (left) [4] and the Bunsen flame burner with aluminum nozzle wedges (right).

3 Results and discussions

Direct images of an edge flame and a Bunsen flame are shown in Fig. 2. The premixed flame path was found through image analysis. Radical intensities along the premixed flame branches were evaluated by taking average values in a neighboring narrow rectangle. In the cases of Bunsen flames (with specific DRs and equivalence ratios), average intensity values at the middle part of the flame branch were obtained. It is notable that the premixed flame branches of an edge flame cover almost entire flammable concentrations. However, local equivalence ratio information on the flame path is unknown. One plausible assumption is that $\phi = 1$ at the triple point (or a junction point) of three flame branches.

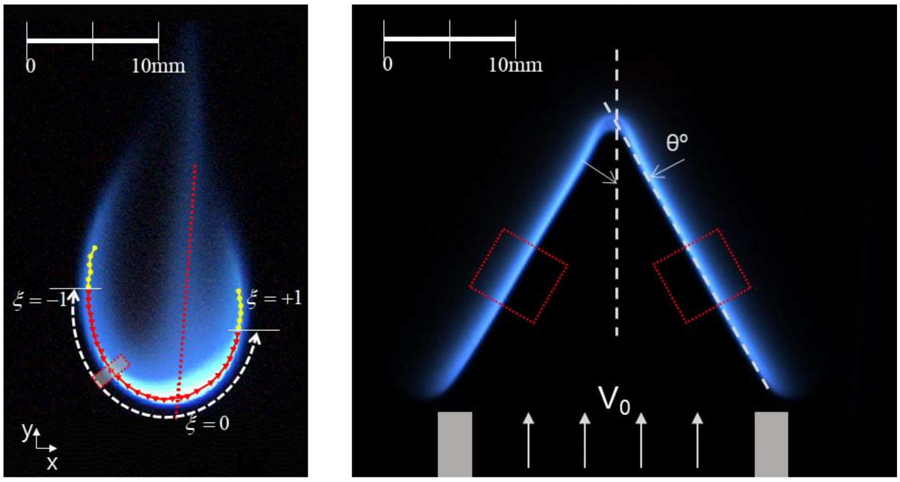

Figure 2: Direct flame image of CH_4-air-N_2 edge flame(left) and premixed Bunsen

Theoretically, the distance ratio from the triple point to a certain point along the premixed flame branch should correspond to a specific ϕ value within the flammable concentrations. Therefore, the relative distance from the triple point to a particular point 'p' on the premixed flame branch, ξ_p, was introduced as follows:

$$\xi_P = \pm \frac{L_{TP \to P}}{L_{RPF} \text{ or } L_{LPF}} \quad \begin{pmatrix} \xi_p = + \text{ , if P is on the RPF branch} \\ \xi_p = - \text{ , if P is on the LPF branch} \end{pmatrix}$$

Distributions of I_{OH}, I_{CH}, and I_{C_2} in the Bunsen flames and an edge flame are plotted concerning ϕ and ξ, as shown in Fig. 3 and Fig. 4, respectively. Two plots showed some similar trends. One is that the peak intensities are located in the fuel-rich conditions in the order of OH, CH, and C_2. However, the chemiluminescence decreased significantly in the fuel-rich conditions of the edge flames.

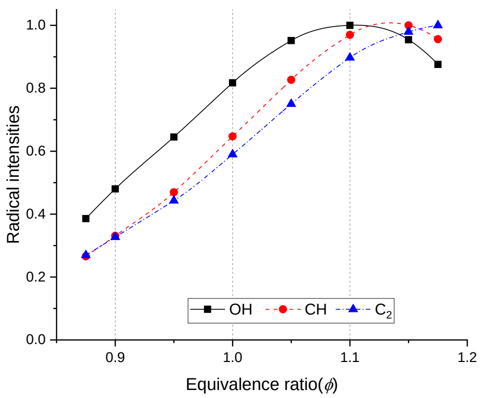

Figure 3: Radical intensity distribution along the equivalence ratio for Bunsen CH_4 premixed flames (DR=0.7 and $\Delta Y_F = 0.05$).

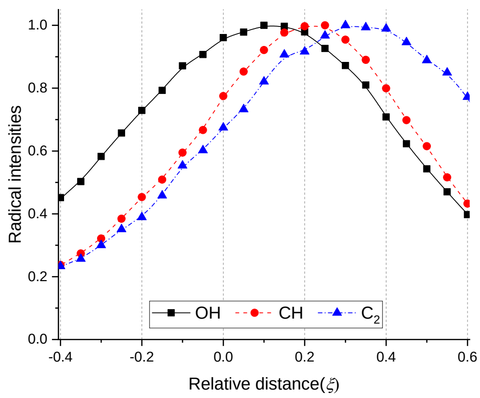

Figure 4: Radical intensity distribution along the relative equivalence ratio (ξ) for a CH_4 premixed edge flame (DR=0.7 and $\Delta Y_F = 0.05$).

The intensity ratios of Bunsen and edge flames are compared, as shown in Fig. 5 and Fig. 6, respectively. The trends of intensity ratios were very similar, i.e., I_{OH}/I_{CH} decreased while I_{C_2}/I_{OH} and I_{C_2}/I_{CH} increased in the fuel-rich conditions.

Regarding the cases of the intensity ratios, it was reported by Kojima [1] that there are fully monotonic variation trends in the cases of undiluted CH_4 Bunsen flames. However, in this study, non-monotonic trends were observed in both Bunsen and edge flames cases. It might be concerned with the reduced flammability limit by N_2 dilution. Extended flammability limits of edge flames are reported by Briones [5].

Therefore, it is acceptable that, as shown in Fig. 3~6, chemiluminescence information from premixed branches of an edge flame is more abundant compared with that from premixed flames such as Bunsen flames. Overall, radical intensities and their ratios obtained from an edge flame were similar to the results obtained from the multiple experiments using the Bunsen flames. Therefore, an edge flame can be used to get the chemiluminescence data more efficiently.

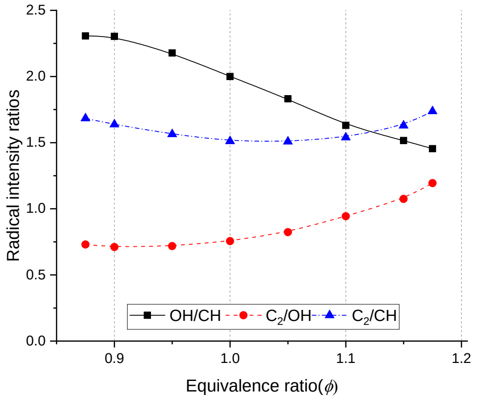

Figure 5: Radical intensity ratios along the equivalence ratio (ξ) for Bunsen CH_4 premixed flame (DR=0.7 and $\Delta Y_F = 0.05$).

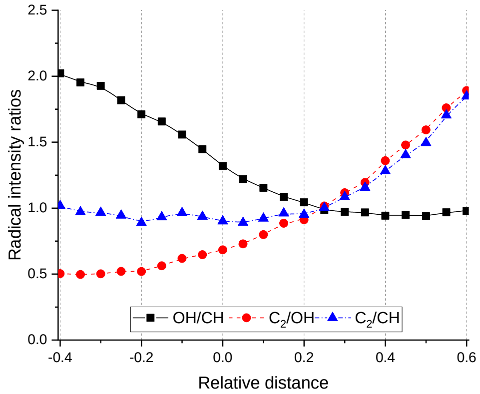

Figure 6: Radical intensity ratios along the relative equivalence ratio (ξ) for a CH_4 premixed edge flame (DR=0.7 and $\Delta Y_F = 0.05$).

4 Conclusions

Radical intensities of OH, CH, and C_2 were obtained using edge flames in a narrow diverging channel, in which small fuel concentration gradients with N_2 dilution were introduced. Similar data could be obtained using premixed Bunsen flames. Commercialized CCD cameras equipped with suitable band path filters were effective in acquiring chemiluminescence data. Conclusively, the results of radical intensities and their ratios were very similar. Therefore, such data can be obtained more efficiently by using edge flame structures, which can be used as reference data to monitor combustion characteristics.

References

[1] Kojima J. Ikeda Y, Nakajima T. (2005). Basic aspects of OH(A), CH(A), and C_2(d) chemiluminescence in the reaction zone of laminar methane–air premixed flames. Combustion and Flame. 140: 34.

[2] Cheng TS, Wu CY, Li YH, Chao YC. (2006). Chemiluminescence measurement of local equivalence ratio in a partially premixed flame. Combust. Sci. and Tech. 178: 1821.

[3] Ayoola BO, Balachandran R, Frank JH, Mastorakos E, Kaminski CF. (2006) Spatially resolved heat release rate measurements in turbulent premixed flames. Combustion and Flame. 144: 1.

[4] Lee MJ, Jung YJ, Kim NI. (2017) Flame-seed structures: Original structures of nonpremixed flames in mixing layers of methane, ethane, propane and DME. Proc. Combust. Inst. 36: 4235.

[5] Briones AM, Aggarwal SK, Katta VR. (2008) Effects of H_2 enrichment on the propagation characteristics of CH_4–air triple flames. Combustion and Flame. 153:367.