A Stable Premixed Methane/Air Sub-Lean Flame Stabilized by Lean Sandwich Flames

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1 Introduction

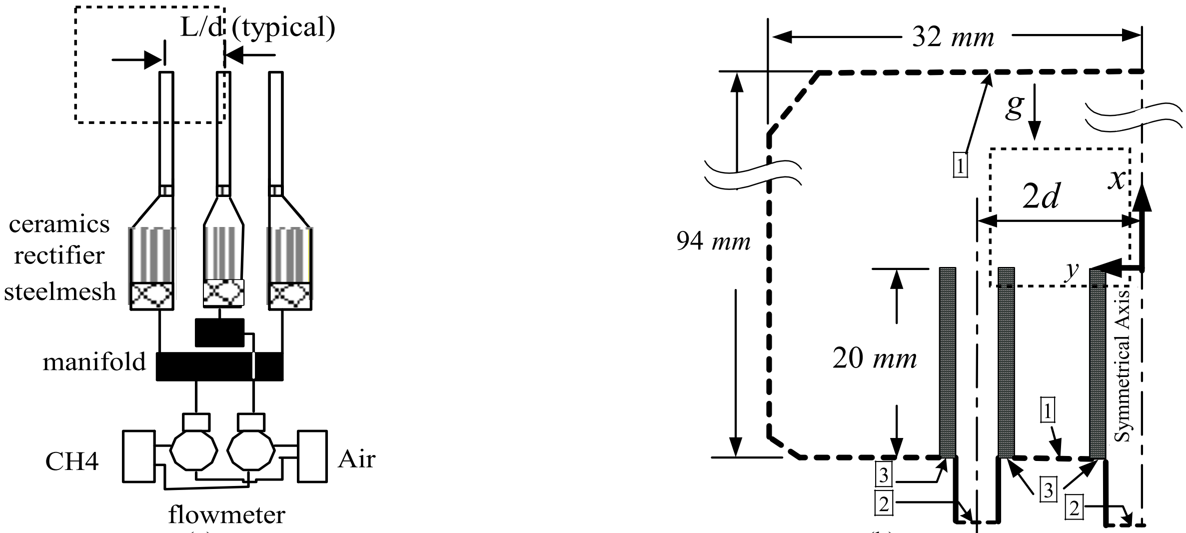
With its abundance on earth, methane, in different forms, is regarded as a major energy source following the fossil oil age. Methane is the major component of the natural gas. Natural gas has been widely used in household stove and industrial heating oven, boiler, etc. Due to its inherent flame instability, the lean and sub-lean methane flame, though with efficient fuel consumption and very low emissions, received much less research attention in the past. Methods of enhancement of combustion stability have been reported in literature [1-5]. The application of burner arrays [6-13] and counterflow flames [14-21] for flame stability enhancement were also reported. Unfortunately, the practical lean and sub-lean combustion systems are complicated due to low reaction rates, extinction, instabilities, mild heat release, and sensitivity to mixing. Thus, a better understanding of the lean and sub-lean methane flame stabilization has become essential for the era of energy crisis.

Recently, Lin et al. [22] showed that the effects of lateral flame impingement created by two identical slot jet flames in adjacency can effectively stabilize the lean premixed methane flame with an equivalence ratio as low as 0.5. The stabilization mechanism results from the lateral impingement of the postflame streams when the two adjacent slot flames were brought closer to each other. Cheng et al. [23] reported a work on flame structure for opposed jet flames of very lean and rich premixed propane-air versus hot products generated by lean hydrogen flames in a DISI engine. The propane-air (φ = 0.60) versus hot products generated a so-called "negative flame speed" flame, which was a diffusion flame formed by reactants diffusing across the stagnation plan and burning in the high temperature lean hot products region. In the conclusion, they drew two prerequisites for this weak flame to exist: (1) high strain rate and excess oxidizer and (2) high temperature hot products from the top jet to support the flame. However, the reason of these prerequisites has not been successfully explained.

The rich-lean flames have also been studied by Seigo et al.[24] and Cheng et al. [25] and they further reported lean and ultra-lean stretched propane-air counter-flow flames. Stretched laminar flame structures for a wide range of propane–air mixtures versus hot products were investigated by laser-based diagnostics and numerical simulation. For most of these propane–air lean mixtures, hot products were needed to sustain the flame from extinction. Two types of flame structures, a lean self-propagating flame and a lean diffusion-controlled flame, were obtained. However, the stabilization mechanism associated with the correlation of hot products and diffusion has not been fully studied and documented.

Unfortunately, the counter-flow flame setup, though good for detailed flame analysis, is much less practical in application. In this study, a practical sandwich burner is arranged to delineate the reasons of the above-mentioned two prerequisites and how the radicals diffuse across the streamlines to help to stabilize the sub-lean flame. The sandwich flames consist of two outboard lean flames and one central sub-lean flame in between with equal slot spacing. To simplify the problem of premixed flame interaction for numerical and experimental studies, we used three 50 mm long times 5mm (also designated as d) wide rectangular slot burners to investigate the structure of the sandwich flames.

Consequently, the structure of the sub-lean sandwich and stabilization mechanism of the sub-lean flame can be successfully simulated and comprehensively discussed.



(a) (b)

Figure 1 (a) The experimental setup of the sandwich burner, (b) The schematic view of calculation domain where it is enclosed by the dash lines in upper left half of Figure 1(a) due to the symmetrical arrangement. The pitch between the slot is 2d, in which d is the width of the burner slot. The boundary conditions are set as $\boxed{1}$ fix pressure, air inlet at 300k or product outlet after calculation, $\boxed{2}$ methane-air mixture with variable φ and ū and $\boxed{3}$ Isothermal of 300k.

2 Results and Discussion

2.1 Flame Shape and Operational Limit

Fig. 2 shows the flame shapes of the sandwich flames with outboard flames burning at a fixed equivalence ratio of φ = 0.88 and the central flame varying from 0.3 to 0.88 at fixed jet spacing of L = 2d and the average burner exit speed of ū = 1 m/s. It is observed that the height of the central flame is increasing as the decrease of the equivalence ratio, especially in the cases of φ = 0.3 and 0.4 sub-lean flames. The tilting of the outboard flames is enhanced with the increase of the equivalence ratio of the central flame as shown from Fig. 2a ~ 2f. The flame of φ = 0.3 is broken at the flame tip.

(a)φ= 0.3 (b) φ=0.4 (c) φ=0.5 (d) φ=0.6 (e) φ=0.7 (f) φ=0.8

Figure 2 The photographs of sandwich flame. The equivalence ratio of the central flame varies from 0.8 down to 0.3 with the support from two constant pilot outboard lean φ = 0.88 flames.

With L/d = 2 spacing, the operational range of sandwich central flame can be extended from lean φ = 0.75 to sub-lean φ = 0.3. Although the sub-lean, φ = 0.3 and 0.4, flames are very weak with faint flame color, the flames are still very stable and are seen to attach to the outboard flames. When the jet spacing is reduced to L/d = 1.5, the operational range can go further down to the equivalence ratio of 0.22. In order to better understand the sub-lean flame structure of the sandwich flame, this study takes a more extreme condition of φ = 0.88 and ū = 0.4 m/sec as the outboard pilot flame and the sub-lean φ = 0.4 and ū = 1 m/sec at the central flame into the simulation. The following sections are the results and the discussion from the simulation. The validation of the results can be found in Ref [26].

2.2 Sub-lean φ = 0.4 Sandwich Flame

The sub-lean sandwich flame is a pilot-flame-aided sub-lean combustion. The assistance from the pilot flames consists of the thermal and radical contributions. Fig. 3 shows the calculated heat release rate with the background of streamlines from the simulation study on φ = 0.4, ū = 1 m/sec at the central and φ = 0.88, ū = 0.4 m/sec at the outboard pilot flames. In order to analyze the properties along the

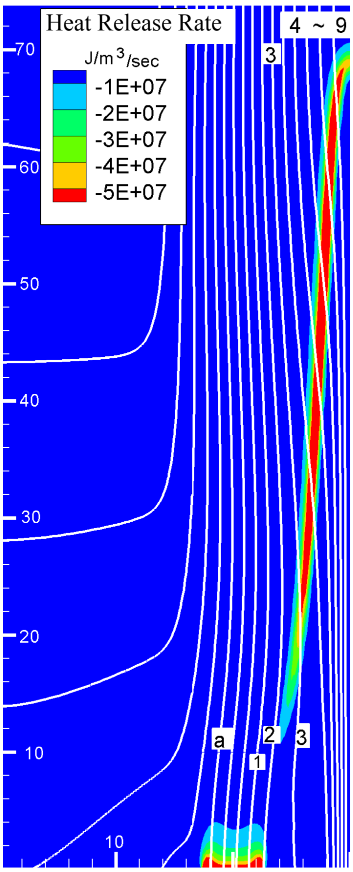


Figure 3 Extreme condition analysis with sandwich flames on φ = 0.4, ū = 1 at central and φ = 0.88, ū = 0.4 at outboard pilot flames.

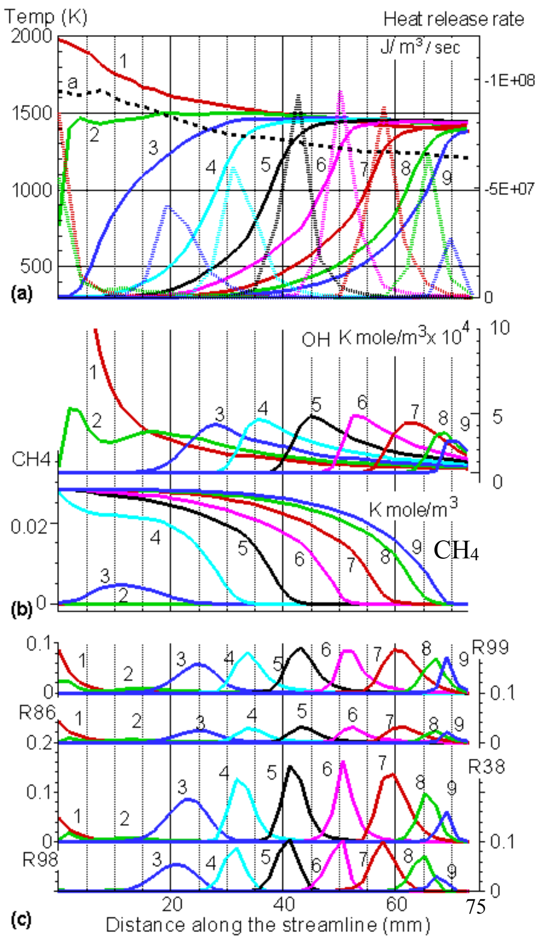


Figure 4 Profiles along the streamlines a, 1,2,3,...,and 9 as noted in Fig. 3.

streamlines, ten characteristic streamlines are designated with names of streamline a, 1, 2, 3, ..., and 9. The properties along each streamline are presented on Fig. 4 with X-axis "distance along streamline". The X-axis of Fig. 4 is counted along the Y-axis direction of Fig. 3. Streamline a is located in the outboard side of the pilot flame but the streamlines 1 to 9 are located at the inboard side of the pilot flame as well as the central flame.

Temperature profile along streamline a is about 250k colder than the inboard side along the streamline 1, as shown in Fig. 4a. The peak temperature of every streamline (4, 5, 6,..., and 9) along the central sub-lean flame is slightly higher than the temperature along the streamline 1. As shown in Fig. 4a , the temperature along streamline 1 and 2 is higher than 1400k but there is no reaction along the streamline 1 and 2 as shown in Fig. 4b and 4c. Along streamline 3, the methane-air mixture is heated by the pilot post flame through streamline 1, at temperature of 1500k ~ 2000k, and streamline 2, at temperature of

1400k instead of downstreamline. For a normal flame, the conductive heat source to the unburnt mixture is from its own downstream combustion due to its rather thinner flame thickness. The flame thickness of the sub-lean sandwich flame is around 25mm while the distances between the two adjacent streamlines 2 and 3, 3 and 4, ..., 8 and 9 are approximately 2 mm only. As shown in Fig. 4a and 4b, the heat release and reaction profiles of streamlines 3, 4, 5, ..., and 9 go up and down one by one consecutively. They perfectly help the adjacent streamline by respectively matching the peak value to the starting point of the consecutive profiles. The temperature profile of streamline 3 goes quite steeply. The streamline 3 is heated by the postflame or streamline 1 and 2 instead of from the heat release of combustion of streamline 3 itself. The heat release peak of streamline 3 is about 10 mm downstream but the distance between the streamlines 2 and 3 is only about 2 mm. Streamline 4 heats up by the streamline 3, 2, and 1, and in the same token streamline 5 by the heat from streamline 4, 3, 2 and 1. In particular, streamline 9 takes so long to heat up to ignition temperature of 1200k because it is located right in the central or far away from the heat source, the pilot post flame.

In streamline 3, the ignition point is almost unnoticeable. The reaction profile of streamline 3 is not that concentrated. In other words, the cumbustion along streamline 3 is relatively mild. Thus the flame thickness is thicker than the rest of the streamlines. The reason is that the major reaction radical OH for streamline 3 is traveling a long distance (at least 15mm) from the pilot flame or streamline 1 and 2 as shown in the upper portion of Fig. 4b before the fresh methane-air mixture is heated up over 1000k for ignition. After the mixture along streamline 3 is heated up to 1000k, the concentration of OH radical is already dramatically reduced and lower than that of streamline 3, which is helping the ignition of streamline 4. Although the concentrations of streamline 1 and 2 are relative high within 15mm along streamline distance, that is of no use for helping the combustion of streamline 3 because the mixture of streamline 3 is too cold to be ignited.

The major reactions of the central flame are plotted in Fig 4c. The flame thickness can be defined from the beginning point of R98: $OH + CH_4 <-> CH_3 + H_2O$ and the end point of R99: $OH + CO <-> H + CO_2$ and it is about 20mm thick along the streamline. It is noticeable that the concentration of CH_4 along streamline 4 has dropped down to 50% at the time when R98 of streamline 4 starts to take place. This means that half of the CH_4 along streamline 4 is participating R98 reaction of streamline 3 by diffusion. From the point of view based on this half, diffusion combustion across streamline 4 to 3, the flame thickness is only about 5mm or about the distance between streamline 3 and 4. As a conclusion, half of the CH_4 concentration is burnt across the adjacent streamline and half of them is burnt along its streamline. At the very last one, streamline 9, there is no across streamline CH_4 migration from the adjacnet one, thus it becomes very weak on reaction R98. That is about half left. In contrary to CH_4, the termination reaction R99 of streamline 9 is as pronounced as streamline 8 regardless of the reduction of CH_4 since there are lots of across streamline R99 reaction from streamline 8 to 9.

2.2 Chemical Pathway

The chemical pathways of the sub-lean flame in the central and its pilot flames in the outboard of the sandwich flames are studied and shown in Fig. 5. In order to clearly distinguish their outstanding characteristics, an extreme condition is studied. This extreme condition consists of $\varphi = 0.4$, $\tilde{u} = 1$ m/sec in the central, $\varphi = 0.88$, $\tilde{u} = 0.4$ m/sec at the outboard, and the spacing L/d = 2 among three slot burners. Fig. 5 shows the comparison of the major reactions of the central sub-lean and the pilot lean flames. For ease of comparison, the central flame reactions are enlarged by 10 times in the figure.

The CH_4 initiation reactions of the central sub-lean flame are mainly through R98: $OH + CH_4 <-> CH_3 + H_2O$ about 75% but R11: $O + CH_4 <-> OH + CH_3$ is only about 18%. For the outboard pilot flame, the CH_4 initiation reactions are averaged among the R98: $OH + CH_4 <-> CH_3 + H_2O$ about 41%, R53: $H + CH_4 <-> H_2 + CH_3$ about 36% and R11: $O + CH_4 <-> OH + CH_3$ about 23%. In contrast, R11 is very weak for the central flame, which is only 7%. From these results, OH is very important for the CH_4 initiation reaction of sub-lean premixed methane mixture.

The termination reaction or the highest heat release reaction is about 70% from the R99: $OH + CO <-> H + CO_2$ in the central sub-lean flame and only 30% from R84: $OH + H_2 <-> H + H_2O$. For the pilot outboard flame, it is found that the termination reactions are equally contributed on R84 about

49% and R99 about 51%.However, CO plays an important role for the sub-lean central flame in heat release.

Among radical recombination reactions, it is found that the reverse reaction of R86: OH + OH <−> O + H_2O becomes important by decomposing H_2O back to OH and R43: H + OH + M <−> H_2O + M almost equals to zero in the central sub-lean flame. In contrast, the radical recombination reaction R43 to form H_2O from OH is far more active than R86 taking H_2O back to OH. This result implies that H_2O is important for supplying additional OH radical for the central sub-lean reaction. It means the radical recombination reaction on sub-lean combustion does not exist and is quite different from the pilot lean φ = 0.88 flame.

Propagation Reaction of the central sub-lean flame is highly dependent on the R38: O_2 + H <−> O + OH, which is about 20 times greater than the second one R3: O + H_2 <−> H + OH. But the difference between these two reactions of the lean pilot flame is only 4.5 times bigger than the other one. This is the reason why the O radical reactions such as R11: O + CH_4 <−> OH + CH_3 and R86: OH + OH <−> O + H_2O are relatively more active than the H radical reactions such as R53: H + CH_4 <−> H_2 + CH_3 and R43: H + OH + M <−> H_2O + M. This is why the excess oxidizer is vital for the sub-lean combustion as mentioned in the Introduction.

The O_2 initiation reaction of the central sub-lean flame depends both on the reaction R36: O_2 + H + N_2 <−> HO_2 + N2 and R35: O_2 + H + H_2O <−> HO_2 + H_2O but the pilot lean flame is more on the R35: O_2 + H + H_2O <−> H O_2 + H_2O.

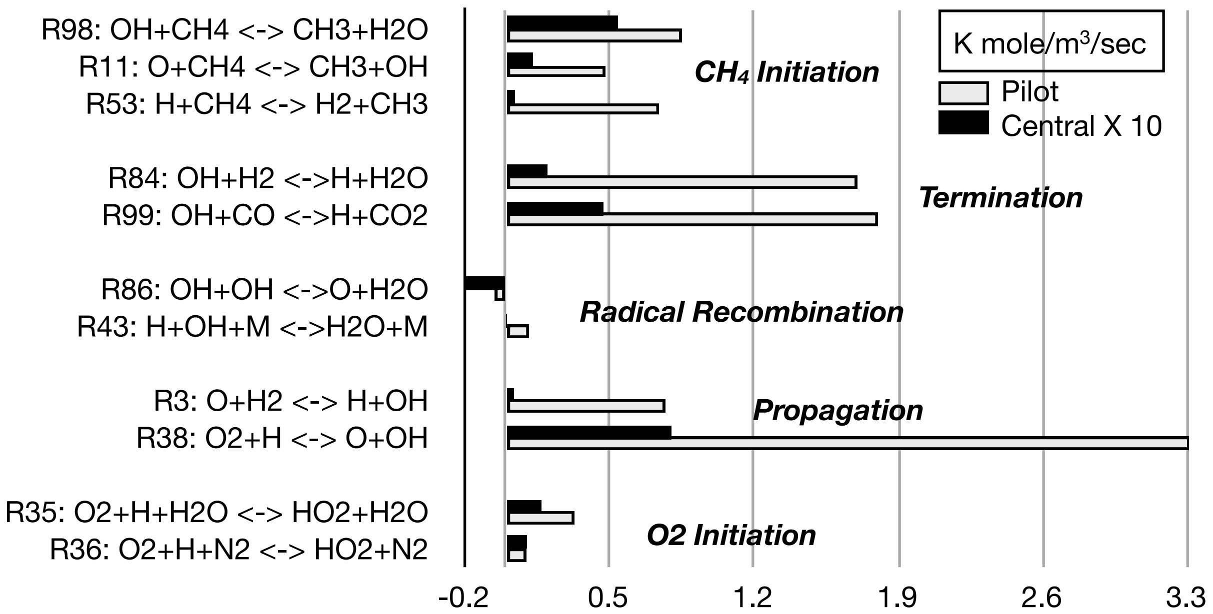


Figure 5 Peak value comparison between the pilot and central flames of significant reactions. The central sub-lean flame mainly relies on R98 and R38 for the CH_4 initiation and propagation reactions. (φ = 0.4, ũ = 1 m/sec for the central, and φ = 0.88, ũ = 0.4 m/sec for the outboard pilot flame)

3 Conclusion

This study successfully demonstrates the feasibility of sustaining stable sub-lean premixed methane/air flame in a practical configuration of sandwich flames and also successfully explains thermodynamic field and chemical species activities of the sandwich sub-lean and lean flames. The simulated results make it possible to explain the stabilization mechanisms such as thermal conducting path and species exchange routes. It is found that the entire sub-lean central flame is mainly sustained by the hot products of outboard lean flames and the base of the sub-lean flame is supported by the residual radicals from the pilot flame.

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