Extinction Mechanism of Swirling Lean Methane-Air Flames

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ABSTRACT

The extinction behavior of the swirling lean methane/air twin flame was studied numerically in terms of the 1-D similarity solution with detailed kinetics. In this study the attention was focused on identifying the elementary reactions which control the extinction, and thus to understand the extinction due to incomplete combustion. Specifically, the behavior of the maximum temperature and the concentration of main intermediate products, such as CO and H₂, at the stagnation plane were studied as the extinction condition is approached. The study has revealed the several interesting behavior; The critical stagnation temperature at the extinction remains almost the same for different counterflow injection velocities and the no-rotating counterflow injection velocity. CO and H₂ profiles at the extinction remain almost the same as well. Furthermore the main species profiles, such as CH₄ and H₂O, also remain the same at these extinction conditions. That is, the extinction occurs with the identical flame structure for the different injection velocities. The balance of three terms in CO and H₂ species conservation equations show that at the extinction condition the diffusion term is larger than the convection term and balances with the reaction term.

1. INTRODUCTION

In the swirling counterflow premixed flame (twin flame) experiment, Chen et al. first showed that the rotating flow increases the flame stability to extend the equivalence ratio at extinction^[1]. The subsequent analytical studies based on the simplified chemical reactions in inviscid flow^[2~5], as well as the numerical study based on the 1-D similarity solution for viscous flow with full kinetics^[6] have revealed that the rotating flow decelerates the axial velocity because of flow divergence and makes the twin flames more stable, thus extending the flammability limit. On the other hand, if the rotating velocity is decreased for the fixed counterflow injection velocities, the twin flames approach the stagnation plane, and finally collapse into the single flame before the extinction. In the flame the reaction zone at the stagnation plane becomes thinner with a decrease in the rotating velocity to reduce the reaction time leading to the extinction. This type of extinction has been observed in other types of counterflow flames, such as axisymmetric flat flame^[7], and tubular flame^[8, 9]. The numerical study based on simplified one-step kinetics has revealed that the unburned reactant increases as the extinction is approached, so the extinction is considered to be caused by the incomplete combustion^[8].

The objective of the present study is to study numerically the extinction behavior of the swirling lean methane/air twin flame in terms of the 1-D similarity solution with detailed kinetics. Specifically, attention is focused on identifying the elementary reactions which control the extinction, and thus to understand the extinction due to incomplete combustion.

2. SIMILARITY SOLUTION FOR VISCOUS ROTATING FLOWS

Figure 1 shows the theoretical model adopted in this study. A premixed mixture flows upward through the lower nozzle and meets the same mixture flowing downward through the upper nozzle. The twin flame is established in the opposing stagnation flow. At the exit of the nozzles, the axial velocity of the mixture is the same for the lower and the upper nozzle. The radial velocity of the mixture is zero, and the mixture has the circumferential velocity of solid body rotation in the same

direction. We adopt the cylindrical coordinates (x, r, θ) , and the corresponding velocities are (u, v, w). The origin of the coordinate is located at the center of the lower nozzle exit plane.

2-1. Basic Assumptions

The assumptions adopted in this study are as follows:

- 1. Flow and flame are steady, laminar and axisymmetric.
- 2. Body forces are negligible.
- 3. The mixture is ideal gas.
- 4. Bulk viscosity is negligible.
- 5. Thermal diffusion is considered only for H and H_2 .

6. Thermodynamic pressure is constant throughout the flow field (Low Mach number approximation)

7. Work done by pressure, viscous dissipation and radiation are negligible in the energy equation.

2-2. Chemical Kinetics and Solution Scheme

The mixture studied is lean methane/air mixture. The equivalence ratio is $\phi = 0.5$. The calculation is performed for the case when the mixture at room temperature (298 K) is injected from the upper and the lower nozzles with the same velocity. The nozzle distance is 2.4 cm. The ambient pressure is latm. For a given equivalence ratio, the rotating velocity is decreased while keeping the counter-flow injection velocity constant. The adopted reaction scheme to describe combustion reactions in the flame is the C1-Chemistry from GRI-Mech1.2. The scheme involves 23 species and 119 elementary reactions. The necessary thermochemical and transport properties are obtained from CHEMKIN data base ^[11~13]. The adopted numerical scheme is basically the one developed by Kee et al. for the onedimensional premixed flame ^[14], and the one modified by M.Nishioka et al. for the present study^[15].

3. RESULTS AND DISCUSSIONS

Figure 2 shows how the maximum temperature at the stagnation plane T_0 changes with the rotating velocity ω for a fixed counterflow injection velocity u_L . The open square indicates the onset of reverse flow, and if the rotating velocity is increased over this value, the reverse radial flow appears^[1~5]. As ω is decreased while keeping u_L constant, T_0 decreases gradually to reach the extinction designated by \times . It is interesting to note that the critical value of T_0 at the extinction remains almost the same for different injection velocities ($u_L = 100 \sim 180$ cm/s) and even the norotating counterflow velocity ($u_L = 82.43$ cm/s). In addition, the behavior of CO and H₂ mole fractions at the stagnation plane is shown in Figs. 3 and 4. Here again, the critical values at the extinction remain almost the same for different injection velocities ($u_L=100 \sim 180$ cm/s) and even the norotating counterflow velocity ($u_L = 82.43$ cm/s).

Figures 5 and 6 show how CO and H₂ distributions, respectively, change with the rotating velocity ω for the fixed counterflow injection velocity of u_L = 140cm/s. As ω is decreased, the two reaction zones of twin flames approach each other, while keeping the almost same profiles. Just before the extinction, the two reaction zones start to merge at the stagnation plane and finally at the extinction, CO and H₂ concentrations jump to certain critical values. At this extinction, the profiles still retain the two peaks. It is interesting to note that these profiles at the extinction remain almost the same for different counterflow injection velocities (u_L =100 ~180cm/s) and the no-rotating counterflow injection velocities (u_L =100 ~180cm/s) and the no-rotating counterflow injection species distributions, such as CH₄ and H₂O, have the same profiles, as is shown in Figs. 9 and 10. That is, the extinction occurs with the identical flame structure for the different injection velocities.

In order to understand the extinction mechanism, the behavior of intermediate products, CO and H_2 , at extinction was studied. Figs. 11 and 12 show, respectively, the balance of three terms in CO and H_2 species conservation equations at the extinction. It should be noticed that even at the extinction condition the diffusion term is larger than the convection term, and it is this term that balances the reaction.

We are still continuing to understand what is the implication of these findings, and to identify the specific elementary reactions that control the extinction process.

4. **REFERENCES**

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