The Combustion Characteristics for CO-CH₄ Blended Fuels

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INTRODUCTION

In this new century of fossil fuel depletion, effectively and environmentally friendly application of low-grade and renewable fuels is an urgent and timely research topics. It is an essential choice to develop combustion technique that effectively burns gasified biomass or low-grade syngas and blended fuels. Most of the gasified fuels have lower calorie and contain compositions, such as methane, carbon monoxide, hydrogen and inerts etc. In the industry and practical applications, due to the low heat release rate, high-grade fuels are usually added to enhance combustion characteristics and reaction mechanisms of single component of high-grade fuels. From the limited research reports, it is clearly shown that the combustion behaviors and reaction mechanisms for the blended fuels is usually completely different from each component and can not be estimated by simple summation based on the proportion and the major combustor design parameters such as the flame velocity and the lean blowout limits can be enhanced by several folds by properly blending the components.

The burning velocity is a major parameter for industrial furnace/combustor design. For most of fuel mixtures, the laminar burning velocity of mixtures can be derived from mass fraction and laminar burning velocity of each composition, according to Yumlu's estimation method [1]. However, in the case of CO-CH₄ mixtures, the estimation method can not predict the value exactly [2]. According to the results proposed by Scholte and Vaags [2], in CO-CH₄ mixtures, they showed that upon addition of methane the burning velocity of carbon monoxide increases and reach its maximum value at about 10 percent methane, and then decreases to the burning velocity of pure methane with increasing of methane concentration. This phenomenon is believed to be caused by the mutation of reaction dynamics induced by H radicals provided by hydrocarbon additive are dominated by CO + OH = CO₂ + H reaction [3] that depends on pressure and temperature [4]. In addition, several experimental and numerical studies about this subject have also been reported [5] - [8]. Nevertheless, the detailed classification of mutual effect between CO and CH₄ and further experimental examination, especially the detailed flame structure, are still warranted.

APPRATUS AND STUDY METHODS

In the present study, the characteristics of artificial blended CH₄-CO fuels are studied with experimental and numerical methods. The parameters with basic properties of premixed jet flames are list in Table 1. In experiments, both premixed CH₄-CO jet and stagnation-flow flames are observed qualitatively. For the stagnation-flow flame, the experiments are carried out on a jet burner consisting of a 20 mm-diameter circular nozzle, from which fuel/air mixture emerges and an adiabatic ceramic stagnation surface. Compressed air, methane, and carbon monoxide from the cylinders are filtered, metered by well-calibrated rotameters, and premixed in the mixing chamber. Honeycombs and mesh screens are installed in the settling chamber to manage the flow quality in order to form the flat flame. A noncatalytic-coated R type (Pt/Pt-13Rh) thermocouple of 25 μ m-diameters is used to measure the temperature.

Images of flame structures are obtained by a highly sensitive 3-chip color CCD camera. The camera shutter time can be adjusted suitably for various flame conditions. The captured images are digitized by the frame grabber for further analysis. On the other hand, PREMIX and SPIN packages of Chemkin accompanied with GRI 3.0 mechanisms are applied to delineate laminar burning velocity and species profile of the flame layer.

RESULTS AND DISCUSSION

The traditional way to define flame qualitative properties is usually based on photographs. Direct images of jet flames are shown in Fig. 1, in which correspond to different mixing levels of CO with CH₄. The blended fuel premixed with stochiometric air emerges from a circular jet. The diameter of the jet is 10mm and the velocity at the jet exit is tuned to 2 m/s. In Fig. 1(a), from appearance, the whole flame of 100% CH₄ premixed jet is blue and the premixed cone can be found clearly. For pure CO premixed flame, the silvery bright white emission from flame can be found in Fig. 1(k). In order to clarify the cases of flame with high luminescence, the shuttle time of the CCD is tuned to 1/5000 sec, and the images are shown in Figs. 1(1) and 1(m). It is interesting to note that the postflame zone becomes yellow in color, and the top angle of flame cone is decreased with the concentration of carbon monoxide is increased (Figs. 1 (b) \sim (j)). The top angle of the flame cone reaches a minimum value in the condition of flame #10 (10% CH₄-90% CO). In addition, the top angle of the flame cone can also be identified as well in pure CO premixed flame and its value is close to that of pure CH₄. In order to simplify the flame characteristics for further analysis, the flat flames with different CO-CH₄ mixtures are also observed and shown in Fig. 2. The distance between the stagnation wall and the stabilization position of the flat flame increases as the concentration of CH₄ in the mixture is decreased. However, the flat flame almost nestles against the stagnation wall in pure CO fuel (flame #11). These phenomena imply that the burning velocity of pure CO is similar to that of pure CH₄. In addition, the burning velocity of CO-CH₄ mixtures in some cases is higher than that of pure methane or pure carbon monoxide. The effects of addition of CH₄ on the burning velocity of mixtures are also examined with the Premix package of Chemkin accompanied with GRI 3.0 mechanisms and shown in Fig. 3. It can be seen that the burning velocity of mixtures reaches its maximum value at about $80 \sim 90$ percent CO (10 ~ 20 percent CH₄). Apparently, this trend of the burning velocity with respect to the concentration of CH₄ the CO-CH₄ mixture is consistent to that proposed by Scholte and Vaags [2].

Stochiometric stagnation flame for each conditions listed in Table 1 is examined numerically with SPIN package of Chemkin. The spatial variations of mole fraction of major species for typical flames, flame #2 and flame #10 are shown in Figs. 4(a) and 4(b) respectively. In Fig. 4(a), for flame #2, it can be seen that CH₄ concentration decrease and H₂O increase start at 0.83 cm from the stagnation wall. CO concentration increase lags a little bit behind CH₄ at 0.8 cm, and increases sharply until OH radical starts increasing. In addition, H_2O also increases prior to CO_2 . These phenomena show that, in flame #2, CH_4 pyrolysis, oxidation and generation of CO go prior to the CO reaction in flame of the blended fuel. In Fig. 4(b), for flame #10, CH₄ and CO oxidation starts almost at the same position, and products including H₂O and CO₂ increase almost coincidentally. Moreover, except conditions listed in Table 1, mixtures with 98% CO- 2% CH4 is also examined for further comparison and shown in Fig. 4(c). In Fig. 4(c), it can be seen that CO starts decreasing prior to CH_4 , and H₂O starts increasing following the appearance of CO₂. In order to show the difference of CO distribution for each condition, the spatial variation of CO as a function of axial distance from the stagnation wall is shown in Fig. 5. For flame $\#1 \sim 7$, it can be seen that the concentrations of CO increase higher than initial first and then decrease following the increase of OH. On the other hand, for flame $\#8 \sim 11$, the concentrations of CO decrease continuously toward stagnation wall while mixtures start reaction. Obviously, the dominant reaction processes and factors for different CO-CH₄ mixtures are noteworthily different. These phenomena shown in Fig. 6 can be interpreted with sensitive analysis on reaction rate. The sensitivity analysis on reaction rate at ignition point have been performed and shown in Fig. 6. The results show that

the OH generation reaction $(H + O_2 \rightarrow O + OH)$ is dominated for high CH₄ concentration flames, flame #1 and flame #6. For the flame with the highest burning velocity, flame #10, the reaction $(OH + CO \rightarrow H + CO_2)$ becomes dominant. The reaction $(OH + CO \rightarrow H + CO_2)$ is the key reaction that influences the properties of CO oxidation in hydrocarbon mixtures and has been studied and documented [4]. In the case of 98%CO - 2% CH4, the key reaction sifts to $(O + CO + M \rightarrow CO2 + M)$ which is the key reaction of oxidation of pure CO is dominated. The reaction $(H + CH_3 + M \rightarrow CH_4 + M)$ which is the initiation of CH_4 reaction becomes more important as the CH₄ concentration is increased. In addition, the reaction $(HCO + M \rightarrow H + CO + M)$ that is the main reaction process of CO production in CH₄ oxidation becomes more unimportant while CO concentration is increased.

CONCLUSION

The combustion characteristics of artificially blended CO-CH₄ mixtures are experimental and numerically studied in the present study. The simulations including the use of PREMIX and SPIN ChemKin packages accompanied with GRI 3.0 mechanisms for burning velocity estimation and simulation of 1-D flame spatial distribution respectively.

The results show that the burning velocity of mixtures reaches its maximum value, which is higher than the maximum burning velocity of CH₄ or CO, at about 10 - 20 percent of CH_4 in CO-CH₄ mixtures. This characteristic is consistent to that proposed by previous study of Scholte and Vaags [2] and can be found in experimental observation as well as estimation in this study. Results also show that the concentration of CH₄ alters the reaction process, reaction rate and flame structures. For the artificially blended CO-CH₄ flame, the flame structure is initiated and dominated by CH₄ reaction when the CH₄ concentration is greater than 40 %. However, when further reducing CH₄ concentration, the chemical kinetics shift toward another component and the reaction of CH₄ becomes less crucial in the overall reaction. In these cases, the oxidations of CH₄ and CO occur almost simultaneously. When the CH_4 concentration reduced to between 10 to 20 percent, the H radicals from CH_4 reaction significantly enhance the CO depletion reaction by OH that significantly increases the overall reaction rate in terms of burning velocity. Finally, the reaction is dominated by CO oxidation while the concentration of CH₄ is less than 10 % and the overall reaction becomes similar to the pure CO reaction.

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	Table 1 Flame parameters						
	Flame	CI14 (0/)	CO (v%)	V(m/s)	V(m/s	V(m/s)	
	number	CH4 (V%)		jet flame	Stagnati	Stagnation	
	1	100	0	2.0	1.0		
	2	90	10	2.0	1.0		
	3	80	20	2.0	1.0		
	4	70	30	2.0	1.0		
	5	60	40	2.0	1.0		
	6	50	50	2.0	1.0		
	7	40	60	2.0	1.0		
	8	30	70	2.0	1.0		
	9	20	80	2.0	1.0		
	10	10	90	2.0	1.0		
	11	0	100	2.0	1.0		
				-		1	
						-	
(a)	(h)	(c)	(b)	(e)	(f)	
(.)	(0)	(•)	(4)	(•)	(-)	
		-	1000				
					-		
(g)		(h)	(i)	(j)	(k)		
					. /		

Fig. 2 The flat flame appearance of flame-(a)1; (b)2; (c)3; (d)4; (e)5; (f)6; (g)7; (h)8; (i)9; (j)10; (k)11.



Fig. 1 The photographs of stochiometric premixed jet flame; refer to Table 1: flame #-(a)1; (b)2; (c)3; (d)4; (e)5; (f)6; (g)7; (h)8; (i)9; (j)10; (k)11 (shuttle time: 1/250sec); (l)10; (m)11 (shuttle time: 1/5000).



Fig. 3 Numerically determined burning velocity as a function of





Fig. 4 Axial distributions of major species for stoichiometric stagnation flame with (a) flame-2, (b) flame-10 and (c) 98%CO - 2% CH₄.



Fig. 5 Spatial variation of CO concentration for conditions listed in table 1.



Fig. 6 Sensitivity analysis on reaction rate at ignition point for flame-1, flame-6, flame-10, and 98%CO - 2%CH₄.