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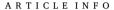


Full Length Article

The effect of CO_2 on the lower flammability limit of C_3H_8 in O_2/CO_2 atmosphere at high temperature and pressure

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Keywords: Oxy-fuel combustion Flammability limit Laminar flame speed

ABSTRACT

In order to provide a reference range for the safe application of C_3H_8 under O_2/CO_2 atmosphere, the lower flammability limit of $C_3H_8/O_2/CO_2$ was studied by calculations. A prediction model based on the limited laminar flame speed principle was used to calculate the lower flammability limit of $C_3H_8/O_2/CO_2$ mixture. The effects of elevated temperature and pressure on the lower flammability limit of C_3H_8 were investigated. How the high CO_2 concentration changes the lower flammability limit was also discussed. Results show that the lower flammability limit of C_3H_8 decreased linearly with the increase of preheating temperatures. The lower flammability limit increased in a logarithmic relation with the increase of pressure. The lower flammability limit increased slightly with increasing CO_2 concentration.

1. Introduction

Climate change is considered to be one of the biggest challenges for human society. The key of controlling climate change is to reduce greenhouse gas emissions [1]. Carbon capture and reliable storage (CCS) technology is recognized as the most effective way to control greenhouse gas emissions. It is also be regarded as a bridge between fossil energy and future renewable energy [2]. The oxy-fuel combustion technology is one of the most promising technologies for carbon reduction [3]. The technical feature of oxy-fuel combustion is that air is replaced by oxygen and circulating flue gas. So the combustion products only contain $\rm CO_2$ and $\rm H_2O_2$, without harmful gases such as $\rm NO_x$ and $\rm SO_2$ [4]. This combustion technology can not only store high concentration $\rm CO_2$ but also can increase the heat efficiency of the boiler/furnace by significantly reducing the heat loss with the flue gas.

In order to improve the application of oxy-fuel combustion, lots of recent research focused on the combustion characteristics of oxy-fuels mixture have been done [5,6], the flammability limit, is one of them. The definition is the concentration of fuel when flame cannot spread stably in the premixed gas. Obviously, the flammability limit can be divided into upper flammability limit (UFL) and lower flammability limit (LFL). There are lots of factors which significantly affect LFL of fuel including initial temperature, initial pressure and dilution. The effect of initial temperature on LFL was studied by S. Kondo et al. [7], G. Cui et al. [8], I. Wierzba et al. [9] and H. Tian et al. [10]. It was found that LFL

decreased with the increasing temperature. The influence of initial pressure was studied by L. Huang [11] through a cylinder chamber. They found that the LFL of methane decreased slightly at elevated pressures. And the effect of different dilution added in air was studied, including CO_2 [10–13], H_2O [13,16] N_2 [14–16], and other fuels [17].

The study of LFL in those articles mentioned before were all measured by experiments. At the same time, numerical study dealing with LFL has been done by lots of researchers. S. Kondo et al. [18,19] revised the Le Chatelier principle and proposed the extended Le Chatelier formula based on lots of experiment data. The extended formula can be used to accurately calculate the flammability limit of combustible gas mixtures containing inert gas CO2 and N2. But the extended formula deeply depends on the experiment results. T. Ma [20] proposed a method that based on the principle of heat balance. M. Wu et al. [21] proposed a new model named variable calculation of adiabatic flame temperature (VAFT) based on calculated adiabatic flame temperature (CAFT) model. This model can be used to calculate the upper flammability limit of alkanes/CO₂/air mixture. G. Pio [22–24], after analysing the CAFT model, heat balance model, limited laminar flame speed principle and other models, believed that the limited laminar flame speed principle [25] was more easier to calculate the flammability limit than others.

Although there were a lot of research about the LFL, only few of them focus on the LFL of fuel under O₂/CO₂ atmosphere. The combustion characteristics under O₂/CO₂ atmosphere are significantly different

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from those in air, which is one of the challenges for the application of oxy-fuel technology [3]. The studies of combustion characteristics under O_2/CO_2 atmosphere are needed for the application of oxy-fuel combustion, such as the flammability limit.

In this paper, a reliable numerical calculation model, based on the limited laminar flame speed principle, was established to calculate the LFL of C_3H_8 under O_2/CO_2 atmosphere. Then the effects of elevated temperature and pressure on the LFL of C_3H_8 were investigated. How the high CO_2 concentration changes the LFL was also discussed.

2. Numerical method

The limited laminar flame speed principle was derived by M. Hertzberg [25], and the basic principle was shown in Fig. 1. For the movement of unburned gas above a spherical flame core propagating, upward in a buoyancy induced flow, there is a stagnation plane in a counterflow configuration which involves a balance between the combustion force and the buoyant force. The former is responsible for the cold gas outward, which is equal to the gradient of the kinetic energy across a propagating flame zone and can be calculated by Eq. (1).

Combustion force
$$= \frac{\Delta(E)}{\Delta x} = \frac{\frac{1}{2}\rho_b S_b^2 - \frac{1}{2}\rho_U S_u^2}{\frac{\alpha}{S_U}} = \frac{S_u^3}{2\alpha} \frac{\rho_u}{\rho_b} (\rho_u - \rho_b)$$
 (1)

where x is the propagation direction, E is the kinetic energy, S_u and S_b are the laminar flame speed of unburned and burned gas respectively, α is the thermal diffusion coefficient, ρ_u and ρ_b are the density of unburned and burned gas respectively.

On the other side, product gases are less dense than reactants, inducing natural convective flows which compete with combustion induced flows. The competition dissipate power from the combustion wave. The buoyancy force can be calculated by Eq. (2)

Buoyancy force =
$$(\rho_u - \rho_b)g$$
 (2)

When buoyancy force begins to exceed the combustion force, the upward propagating wave is blown off. It indicates that when the two competition forces are in balance, the concentration of fuel is equal to the flammability limit under this condition. Thus, the limiting laminar flame speed was derived from Eqs. (1) and (2) and shown in Eq. (3)

$$S_{u,lim} = \left[2\alpha g \frac{\rho_b}{\rho_u} \right]^{1/3} \tag{3}$$

The LFL can be calculated with the comparison of s_u and $s_{u \cdot lm}$ in the following way. Fig. 2 shows the calculation process of LFL. Firstly, the initial conditions were settled, then the s_u and some basic parameter (such as the adiabatic flame temperature, gas density, combustion product density and thermal diffusion coefficient) were calculated. Secondly, the $s_{u \cdot lim}$ was calculated. Thirdly, compared the s_u with thes $s_{u \cdot lim}$. If the former was greater than the latter, the fuel was combustible, and the concentrate of fuel should be reduced. If not, the concentration of fuel should be increased. If the two speeds are

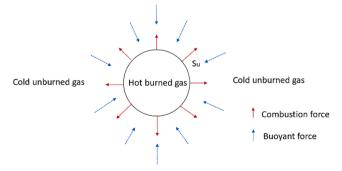


Fig. 1. Basic principle of limited laminar flame speed.

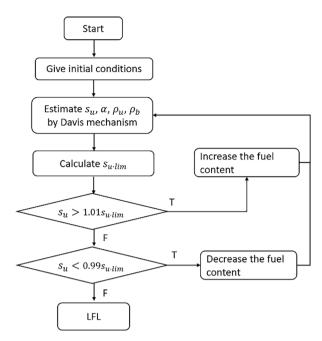


Fig. 2. Schematic representation of the calculation model.

approximately equal to each other (this paper is 1%), the fuel concentration can be regarded as the LFL under this condition. The reason why we chose 1% is according to our algorithm, when the difference of two speeds is larger than the threshold, concentration of fuel will be changed and the new concentration will be taken into calculation again until the difference is smaller than the threshold. We tried many thresholds, such as 0.1%, 0.5%, 1.0%, 1.5% and 2.0%. Finally, 1% is the best choice to reduce the number of iterations and do not affect the calculation accuracy. If the threshold is too small, the calculation will be endless.

In this manuscript, the laminar flame speeds were calculated in adiabatic condition. In fact, the flammability limits are affected by many parameters, such as radiative heat loss, flame stretch, Lewis number, ignition energy. The model used in this manuscript is an approximate method to consider the effects of the flame stretch and Lewis number. The flame stretch in ignition process is due to the spherical expansion caused by combustion and vertical flow caused by buoyancy. The limiting laminar flame speed (Eq. (3)) was developed by considering the balance between the rate of energy generation at the forefront of adiabatic flame propagation and the rate of energy loss from buoyant convection and flame stretch. In the calculation of the laminar flame speed, the real Lewis number was used, so the effects of Lewis number and flame stretch were considered in Eq. (3). For the radiative heat loss, Hertzberg M discussed the effect of radiative heat loss on the flammability limit [26]. He thought radiation heat loss is significant for highly emissive mixture, however, the radiation emission for C₃H₈/O₂/CO₂ mixture is low. Hu et al. [27] found that the radiative heat loss caused by CO₂ is insignificant, as it only accounts for less than 7% of the total heat loss at the LFL points. Thus, the effect of radiation heat loss on LFL can be neglected in the present work. Most prediction models of the flammability limits including the present model assumed that a flame kernel is formed directly after ignition. This means that the ignition energy is so high that the LFL is nearly not affected by the ignition energy, which is very closed to real ignition process in the experimental measurement of LFL. The ignition voltage is 14 kV which is much higher than the minimum ignition voltage. Generally, the effect of the ignition energy on the LFL was neglected in the prediction models

In this paper, the calculation model was performed by Cantera based code *FreeFlame*, which was suitable for the one-dimension, adiabatic, and premixed laminar flames estimation. Cantera [28] is an open-source suite of tool for problems involving chemical dynamics,

thermodynamics, and transport equations. It can be used to calculate thermal properties, transport properties, chemical equilibrium, nonideal equations of state, one-dimensional flame, etc. The detailed kinetic mechanism used is the Davis mechanism [29]. Which have been used for natural gas/hydrogen blends at 1–35 atm [30], for propane at 300-1200 K [31], for propane/air at 1–2 bar [32]. And according to our former research [33], the simulation parameters ratio, slope, and curve were set as 3, 0.06, and 0.12 respectively to calculate s_u at a high accuracy. The length of the calculation domain was 12 cm to ensure the completion of all combustion reactions.

As mentioned before, LFL is influenced by many factors including preheating temperature, pressure and dilution gas. Fig. 3 shows the experimental and calculated LFL of $C_3H_8/O_2/CO_2$ in various CO_2 concentrations (from 10% to 80%) at 300 K and 1 atm.

The concentration of CO₂ was calculated by Eq. (4).

$$CO_2 = \frac{n_{CO_2}}{n_{CO_2} + n_{O_2}} \times 100\% \tag{4}$$

Experimental results and calculated results show that the LFL increased slightly with the increasing CO2 concentration. The calculated values were closed to the experimental results especially at low $\rm CO_2$ concentration. In order to quantify the error of the method, mean absolute error (MAE) was introduced, and it could be calculated in Eq. (5).

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \frac{|e_i - c_i|}{e_i}$$
 (5)

where e_i is the experimental value, c_i is the model prediction result, and n is the test number.

After calculation, the MAE between the predicted value and the experimental value was 7.73%, which was mainly due to the large gap at high $\rm CO_2$. And it can be concluded that the model can predict LFL of $\rm C_3H_8/O_2/CO_2$ at a high accuracy when concentration of $\rm CO_2$ is under 60%.

3. The results and discussions

3.1. Effect of high initial temperature

The initial temperature is an important factor affecting the combustion process. It not only affects the rate of oxidation reaction between fuel and oxygen, but also the heat dissipation from the system to the environment. In order to study the effect of preheating temperature, the LFL under different concentration of $\rm CO_2$ were calculated at preheating temperature changed from 300 to 500 K. The results were shown in Fig. 4.

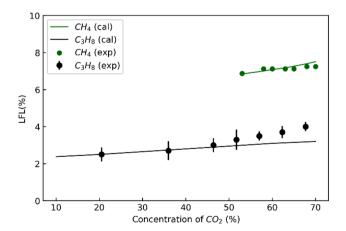


Fig. 3. The comparison of experimental results and calculated results, in which the experimental results of C_3H_8 from [27], CH_4 from [41], C_2H_6 from our unpublished experimental data and all calculated results from our model.

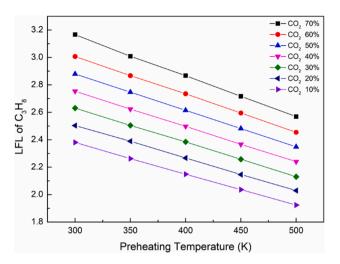


Fig. 4. LFL under different concentration of CO_2 at 300–500 K.

In Fig. 4, the LFL changed linearly with the preheating temperature. Table 1 lists the linear regression equation between the LFL and preheating temperature at 300 K, 350 K, 400 K, 450 K and 500 K.

As shown in Table 1, R2 value was above 0.999 at each temperature, which means that the LFL has a strong linear correlation with the preheating temperature, which was consistent with the conclusions drawn by many scholars [7,10].

As shown in Fig. 4, as the preheating temperature increasing, the LFL gradually decreased, which made the flammable range wider. It can be explained that the heat required to raise the temperature of 1 mol mixture from the preheat temperature T₁ to the flame temperature T₂ was equal to the heat released by combustion of 1 mol of unburned gas. Wierzba et al. [34]. suggested that the flame temperature T₂ at LFL is constant regardless of the preheating temperature for different syngas mixtures. And S. Li [35] found this assumption is still valid at high inert dilution conditions. While Wang et al. [36] prove this assumption is still valid at inert dilution of CO₂. Which means the heat required to raise the temperature of 1 mol mixture from the preheat temperature T1 to the adiabatic flame temperature T2 was equal to the heat released by combustion of 1 mol of unburned gas. So, when other conditions remain unchanged and the preheating temperature T₁ increase, the heat required for mixed gas's temperature rising to T2 decrease, as well as the required of fuel. Therefore, the LFL drops.

This phenomenon could be explained by the molecular dynamics. At the LFL point, oxygen is rich and fuel is deficient. With the increase of preheating temperature, the kinetic energy of fuel and oxygen molecules increase and the molecular collisions are intensified. So, the LFL decreased with the rising temperature.

On the other side, The LFL gradually decreased with the increase of the preheating temperature but the increase rate is slight. For example, at 30% CO₂ concentration, the LFL was 2.63% at 300 K. While when the preheating temperature raised to 500 K the LFL was 2.13%. The preheating temperature increased 66.6% but the LFL only decreased 0.5%. It indicates that the preheating temperature has a weak influence on the

Table 1 Linear equation of LFL and preheating temperature under different concentrations of CO_2 dilution atmosphere.

CO ₂ %	The linear regression equation	R^2
70%	LFL = -0.0030 T + 4.0557	0.9998
60%	$LFL = -0.0028 \ T + 3.8337$	0.9999
50%	LFL = -0.0027 T + 3.6766	1
40%	LFL = -0.0026 T + 3.5233	1
30%	LFL = -0.0025 T + 3.3797	0.9999
20%	$LFL = -0.0024 \ T + 3.2198$	0.9999
10%	$LFL = -0.0023 \ T + 3.0619$	0.9999

LFL.

3.2. Effect of initial pressure

The influence of initial pressure on the flammability limits is not as straight forward as that of initial temperature [37]. Mostly, a decrease in the initial pressure will narrow the flammable range by increasing the LFL, such as CH_4 /air mixtures [8,11]. However, there are some notable exceptions to this rule. The LFL of propane/air mixtures go up slightly at the first stage of pressure increase (0–20 bar) [38]. The LFL of H2/air mixtures was found to show an initial narrowing at pressures up to 20 bar, as well as the CO/air mixtures show the same trend as pressures up to 125 bar [39]. So how the LFL of propane/ O_2/CO_2 mixtures changes with increasing pressure is going to discuss.

Fig. 5 shows the change of LFL when the initial pressure changed from 1 atm to 30 atm at different CO2 concentrations at 300 K. As shown in Fig. 5, as the pressure increasing, the LFL at each CO2 concentration increased, and the change rate varied with the pressure. When pressure changed from 1 atm to 5 atm, the LFL raised sharply. While when pressure changed from 5 atm to 30 atm, the LFL raised more gently, which showed as the pressure increasing, the changing rate of the LFL gradually decreased. It can also be seen from Fig. 5 that the LFL raise with the CO₂ under the same initial pressure. this is owing to the effect of CO₂, which would be discussed in the following part. There are two reasons why LFL of propane/O2/CO2 mixtures increases with the increasing pressure. Increasing pressure speeds up the chemical reaction [11 16], but more heat is needed to heat the unburned area to maintain flame propagation [36]. Furthermore, according to the research of Hu et al. [33], the element reaction $H + O_2 + H_2O \le HO_2 + H_2O(R14)$ is the main inhibition reaction of C₃H₈ combustion under O₂/CO₂ atmosphere. The forward reaction consumes O2 and H groups, inhibiting the combustion reaction significantly. And the increasing pressure significantly promotes the forward direction of R14, which inhibits the combustion reaction. Therefore, based on the above two aspects, the LFL of propane/O2/CO2 mixtures increased with the initial pressure.

Table 2 lists the fitting formula. The LFL changed logarithmically with the pressure. The R^2 were all above 0.9, showing a strong logarithmic relation of LFL with pressure. And the logarithmic relation between LFL with pressure is also be found by L. Huang et al. [9], Kondo et al. [40].

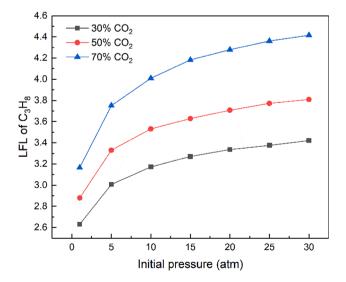


Fig. 5. The change of LFL versus the initial pressure under different ${\rm CO_2}$ at 300 K.

Table 2
Regression equation of LFL and initial pressure at different CO₂.

CO ₂ %	The regression equation	R^2
30% 50% 70%	$ \begin{aligned} \text{LFL} &= 0.2328 \text{ln}(\text{p}) + 2.6332 \\ \text{LFL} &= 0.2748 \text{ln}(\text{p}) + 2.8851 \\ \text{LFL} &= 0.3711 \text{ln}(\text{p}) + 3.1628 \end{aligned} $	0.9932 0.9995 0.9996

3.3. Effect of CO2

Due to the differences of physical and chemical properties between N_2 and CO_2 , the combustion characteristics of $C_3H_8/O_2/CO_2$ and that of $C_3H_8/O_2/N_2$ are significantly different. As well as the dilution effect, thermal effect and chemical effect of CO_2 on LFL were analysed in this section.

3.3.1. The dilution effect of CO₂

In order to exclude the influence of CO_2 chemical property, a virtual substance FCO_2 have been introduced. The physical and other properties of FCO_2 and CO_2 are completely the same, but the former does not participate in any reactions. For $C_3H_8/O_2/CO_2$ gas mixtures, the product are CO_2 and H_2O . One part of CO_2 is derived from the oxidization of C atoms in C_3H_8 . The other CO_2 is originally contained in the mixture. For $C_3H_8/O_2/FCO_2$ mixture, the products are composed of CO_2 , CO_2 and CO_3 . Among them, CO_2 is produced by the combustion of CO_3 atoms of CO_3 and the CO_3 is originally contained in the mixture.

Fig. 6 shows the LFL at different FCO $_2$ concentration at 300–500 K. The LFL increases slightly with the increase of FCO $_2$. This law was similar with that found by M. Wu et al. [18]. M. Wu et al found that the stoichiometric number of combustion reaction at the LFL and UFL changes due to the addition of inert gas, which make the UFL gradually decrease and the LFL gradually increase, eventually leading to the reduction of the combustible range. The most significant effect of increasing FCO $_2$ on the combustion is that the decrease of the oxygen concentration.

At LFL, it is oxygen-enriched and fuel deficient, so the oxygen concentration does not restrict the flammability. That means the dilution effect of CO_2 on LFL is quite small. As shown in Fig. 6, the FCO_2 concentration increases from 10% to 80%, but the increase of LFL is less than 1%.

3.3.2. The effect of CO₂ thermal property

The thermal property of CO₂ has an impact on combustion, which affects LFL. It has been found [33] found that the difference of laminar

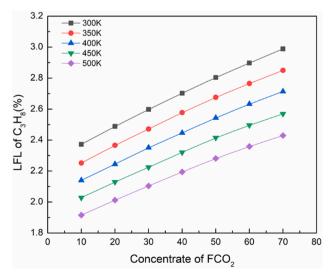


Fig. 6. LFL at different FCO2 concentration at 300-500 K.

flame velocity between $C_3H_8/O_2/CO_2$ and $C_3H_8/O_2/N_2$ is mainly due to the influence of the thermal property of CO_2 . In order to exclude the effects of CO_2 chemistry, FCO_2 was still used. LFL of $C_3H_8/O_2/FCO_2$, $C_3H_8/O_2/CO_2$ and $C_3H_8/O_2/N_2$ were calculated respectively. Since both FCO_2 and N_2 were inert gases and didn't participate in combustion, their effect on LFL differed only in the thermal property.

Before we discuss the effect of thermal property of CO₂, there shows the constant-pressure specific heat(c_p) of three gases at different temperature in Fig. 7. It can be seen that as the temperature increase, c_p of CO₂ increases significantly, but that of the other two gases (N₂ and O₂) increase slightly. The c_p of O₂ is a little larger than N₂. On the opposite, the c_p of CO₂ is much larger than N₂ and O₂ especially at high temperature. According to the aforementioned principle, the combustion reaction proceeds only when the heat released by the combustion reaction can cause the unburned fuel's temperature to exceed the threshold temperature, which is usually the adiabatic flame temperature T_{ab} .

As shown in Fig. 8, LFL of C₃H₈/O₂/FCO₂ and C₃H₈/O₂/CO₂ gradually increase with the dilution concentration, but a slight decrease with $C_3H_8/O_2/N_2$ atmosphere. And it has been found that the LFL of O_2/CO_2 under 350 K is consist with Kondo's experiment data [19], which prove the accuracy of our model again. At low concentration, LFL under O₂/N₂ atmosphere is almost equal to the other two. But with the increasing of dilution, the gap between O2/N2 atmosphere with the other two is getting larger. And it's mainly owing to the increasing of C₃H₈/O₂/FCO₂ and C₃H₈/O₂/CO₂ s' LFL instead of the decreasing of C₃H₈/O₂/N₂'s LFL, which is quite small. The large c_p of CO₂ (or FCO₂) makes CO₂ (or FCO₂) absorbs more heat released by combustion than N2, resulting in less heat absorbed per mole of unburned fuel. Therefore, the LFL under O2/CO2 (or O₂/FCO₂) atmosphere is higher than that under O₂/N₂ atmosphere. And it's interesting to find that the LFL under O2/N2 atmosphere is decreasing slightly (less than 0.2%) with the increasing dilution concentration. The reason why it decreases slightly is that the cp of O2 is a little larger than N2 and when the concentration of O2 is larger than 21% (which is higher than the oxygen in the air), the more N2 will absorb less heat, which makes the LFL decrease slightly.

As shown in Fig. 8, although the difference between $C_3H_8/O_2/CO_2$ and $C_3H_8/O_2/FCO_2$ is not as obvious as that between $C_3H_8/O_2/CO_2$ and $C_3H_8/O_2/N_2$, it also raises with the increasing of dilution concentration, especially at high dilution concentration. The difference is owing to the chemistry effect of CO_2 . In the next section, the chemistry effect was discussed.

3.3.3. The effect of CO_2 chemistry

 ${\rm CO_2}$ participates in reactions in the combustion process of ${\rm C_3H_8}$ and affects the LFL. The effect of ${\rm CO_2}$ chemistry can be obtained by

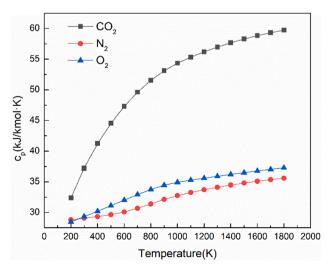


Fig. 7. c_p of O_2 , N_2 and CO_2 at different temperature.

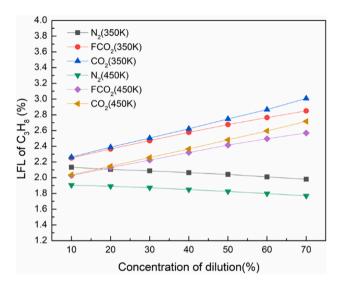


Fig. 8. LFL of $C_3H_8/O_2/FCO_2$, $C_3H_8/O_2/CO_2$ and $C_3H_8/O_2/N_2$ versus dilution concentration at 350 K and 450 K.

comparing the difference of LFL under O_2/CO_2 and O_2/FCO_2 atmospheres. The calculation results were shown in Fig. 9(a–f). In order to intuitively investigate the impact of CO_2 chemistry on LFL at different temperature, the concept of relative LFL difference (\triangle LFL) was introduced. The calculation formula was shown in Eq. (6).

$$\Delta LFL = \left| \frac{FL_{CO_2} - FL_{FCO_2}}{FL_{CO_2}} \right| \times 100\% \tag{6}$$

where FL_{CO_2} is the flammability limit of $C_3H_8/O_2/CO_2$, FL_{FCO_2} is the flammability limit of $C_3H_8/O_2/CO_2$

The change of $\triangle \text{LFL}$ with preheating temperature was shown in Fig. 10.

As shown in Figs. 9 and 10, the larger the concentration of CO_2 is, the greater its chemical influence on the LFL is, regardless of initial temperature. From the comparison in Fig. 9, the difference of LFL caused by FCO_2 and CO_2 is the largest when the concentration of dilution gas is 70%. And as the dilution decreases, the difference gradually decreases to zero. For example, at 70% dilution gas, the relative difference is 5.5%, but it is less than 0.5% at 10%.

The results of LFL in different pressure were shown in Fig. 11. It showed the same change rule with that in different temperature: the higher the concentration, the greater the effect of ${\rm CO_2}$ chemical properties.

It can be concluded that under certain initial temperature and pressure, the higher the CO_2 concentration is, the greater the effect of CO_2 chemical properties is. This phenomenon can be explained by the principle of chemical kinetics. From the research of F. Liu [15], the elementary reaction $OH + CO <=> CO_2 + H$ (R99) is the main reaction involving CO_2 . So, the chemical property of CO_2 influences LFL mainly through this reaction. High concentration of CO_2 causes the R99 reaction proceed in the opposite direction, resulting in the consumption of a large amount of H radial. The H radial is the major reactive radial of the radical reaction $OH + O_2 <=> OO + OH(R1)$. When the H radials are consumed in a large amount, R1 reaction is suppressed. R1 is the key elemental reaction of hydrocarbon fuel combustion [33], the suppression of reaction leads to a significant reduction in the combustion intensity. And in order to make enough H radials participate in the reaction, more fuel is required, resulting in increase of the LFL.

4. Conclusion

In this paper, LFL of $C_3H_8/O_2/CO_2$ was studied by a reliable numerical calculation model. Firstly, Cantera on Python platform was used

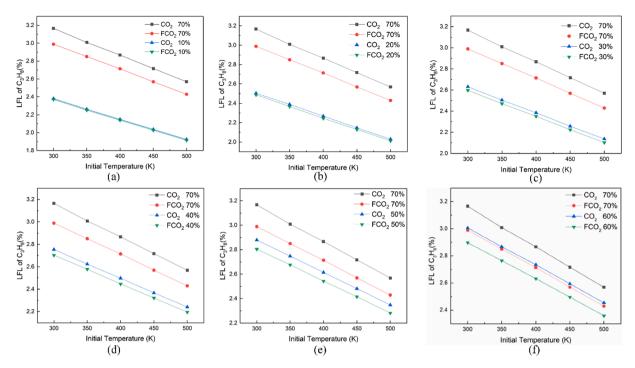


Fig. 9. LFL of C₃H₈/O₂/CO₂ and C₃H₈/O₂/FCO₂ at different preheating temperature.

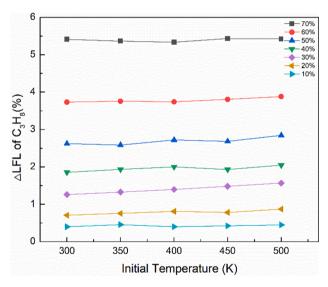


Fig. 10. △LFL with preheating temperature.

to build the LFL calculation model, which is based on the limited laminar flame speed principle. After verifying the accuracy with experiment result, the model was used to study the influence of preheating temperature, initial pressure and CO_2 on LFL. It was found that the LFL decreases linearly with the increasing preheating temperature, while raises logarithmically with the increasing initial pressure. The effects of CO_2 were also studied, including CO_2 dilution effect, thermal effect and chemical effect. It was found that the dilution effect mainly changes LFL by reducing the oxygen concentration, while the thermal property of CO_2 makes LFL much higher than that under O_2/N_2 , which is owing to more heat absorbed by CO_2 than N_2 . The chemistry effect of CO_2 on the LFL is mainly from the inhibition of the number of H radials. Higher CO_2 concentration inhibits more H radials, resulting in a significant reduction in the flammable area.

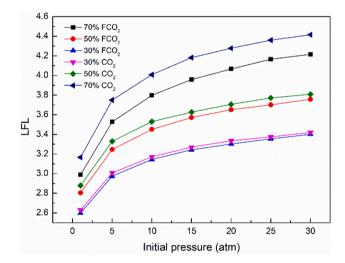


Fig. 11. LFL of $\rm C_3H_8/O_2/CO_2$ and $\rm C_3H_8/O_2/FCO_2$ in different pressure under 350 K.

CRediT authorship contribution statement

Hao Wei: Writing – original draft, Investigation. **Xianzhong Hu:** Conceptualization, Methodology. **Bingrong Huang:** Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (No. 51706037).

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