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Effects of Diluents on Cellular Instabilities in Outwardly Propagating Spherical Syngas–Air Premixed Flames

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ABSTRACT

Experiments were conducted in a constant pressure combustion chamber using schlieren system to investigate the effects of carbon dioxide/nitrogen/helium diluents on cellular instabilities of syngas–air premixed flames at room temperature and elevated pressures. Laminar burning velocities and Markstein lengths were calculated by analyzing high-speed schlieren images at various diluent concentrations and equivalence ratios. Experimental results showed substantial reduction of the laminar burning velocities and of the Markstein lengths with the diluent additions in the fuel blends. Effective Lewis numbers of helium-diluted syngas–air flames increased but those of carbon dioxide- and nitrogen-diluted syngas–air flames decreased in increase of diluents in the reactant mixtures. With helium diluent, the propensity for cells formation was significantly diminished, whereas the cellular instabilities for carbon dioxide-diluted and nitrogen-diluted syngas–air flames were not suppressed.

Key Words: Cellular instability, Effective Lewis number, Premixed combustion, Syngas–air flame

1. Introduction

In recent year, syngas is being recognized as an attractive new fuel and expected to play an important role in future energy demand. Syngas mixtures could be a proposal of the extension of flame stability limit, the improvement of performance, the reduction of pollutant emissions in lean combustion and mobile combustion systems, and the reduction of CO_2.

Cellular instabilities could be one of the main reasons for gas explosion. The cellular instabilities can be caused by body-force effect, hydrodynamic effect, and diffusive-thermal effect [1]. In this study, the body-force effect is not significant and can be neglected. The hydrodynamic effect is caused by the density jump across the flame and depended on the thermal expansion ratio and the flame thickness. The diffusional-thermal effect results from the diffusive disparity of heat conduction from the flame and reactant diffusion towards the flame and depended on the effective Lewis number.

For understanding about cellular characteristics of the syngas–air flame, this study focuses on the effects of diluent additions, by adding 10%, 20%, 30% and 40% (by volume) of CO_2, N_2, He in the reactant mixtures, on cellular instabilities of $50H_2$:50CO syngas–air premixed flame at room temperature and elevated pressures using freely propagating spherical flames method.

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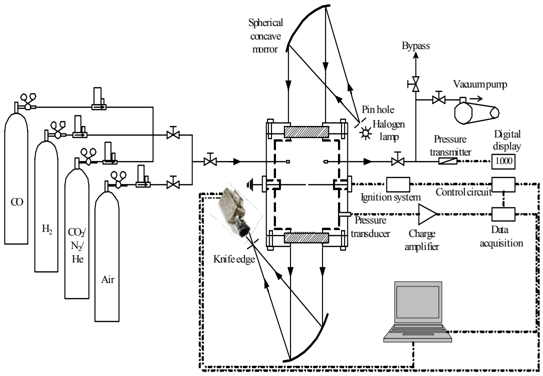

Fig. 1. Schematic representation of experimental setup.

2. Experimental and computational specifications

2.1 Experimental setup and procedure

The experiments were conducted in a cylindrical chamber as shown in Fig. 1. The spherical flames were recorded by a high-speed digital camera of the schlieren system.

The dilution ratio is defined as

$$X_{diluent} = \frac{V_{diluent}}{V_{diluent} + V_{fuel}} \tag{1}$$

where $V_{diluent}$, V_{fuel} are the volume fractions of diluents and fuel in the reactant mixtures.

2.2. Laminar burning velocity and Markstein length

For a spherically expanding flame, stretched flame velocity is calculated as

$$S_n = \frac{dR}{dt} \tag{2}$$

where R is the instantaneous radius of the flame in schlieren photographs and t is the time. Flame stretch rate, α, is defined as

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{R}\frac{dR}{dt} = \frac{2}{R}S_n \tag{3}$$

where A is the surface area of flames.

The flame speed can be related to the flame stretch rate through the linear relationship as

$$S_l - S_n = L_b \alpha \tag{4}$$

where S_l is the unstretched flame speed, and L_b is burned gas Markstein length. The unstretched laminar burning velocity is obtained by

$$S_u^0 = S_l\left(\frac{\rho_b}{\rho_u}\right) \tag{5}$$

where ρ_u,ρ_b are the densities of the unburned and burned mixtures, $\sigma = \rho_u/\rho_b$ is the thermal expansion ratio. The characteristic flame thickness is $l_f = (\lambda/C_p)/(\rho_u S_u^0)$, where λ and C_P are the thermal conductivity and the specific heat at 1200 K, which is approximately the average of the freestream and flame temperatures.

The PREMIX code was used to calculate S_u^0 of diluted syngas - air flames. The chemical mechanism used in this study was the model of Sun et al. [2].

2.3. Effective Lewis number

The fuel Lewis number of the reactant is

$$Le_F = 1 + \frac{q_{H_2}(Le_{H_2} - 1) + q_{CO}(Le_{CO} - 1)}{q} \tag{6}$$

The effective Lewis number is defined as

$$Le_{eff} = 1 + \frac{(Le_E - 1) + (Le_D - 1)A_1}{1 + A_1} \tag{7}$$

where Le_E and Le_D are the Lewis numbers of excessive and deficient reactants. Fig. 2 shows that Le_{eff} in the CO_2- and N_2-diluted syngas - air flames always decrease, whereas those in the He-diluted syngas - air flames always increase. It means a suppressant of the diffusional-thermal instability is only obtained for the flames when increasing contents of He in the reactant mixtures.

2.4. Critical Peclet number

For lean mixture, the critical Peclet number was described by Law et al. [3]

$$Pe_{cr} = \omega^{-1}[Q_1 + \beta(Le_{eff} - 1)Q_2/(\sigma - 1) + \Pr Q_3] \tag{8}$$

where ω, Q_1, Q_2, Q_3 are the constant numbers, Pr is the Prandtl number and β is the Zeldovich number.

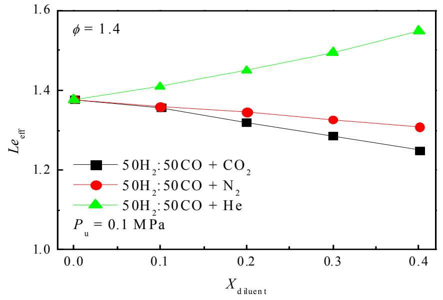

Fig. 2. Effective Lewis numbers of diluted syngas - air flames for Φ = 1.4 at P_u = 0.1 MPa.

3. Results and discussion

3.1. Unstretched laminar burning velocities and Markstein lengths

Fig. 3 shows experimental and predicted S_u^0 for the diluted syngas - air flames for Φ = 1.0 at P_u = 0.1 MPa. The measured and computed S_u^0 showed good agreement. The results indicate that all diluents cause S_u^0 to decrease as the concentrations of diluents increase.

As mentioned above, if L_b > 0, the stretched flame speed decreases with the increase of the flame stretched rate, thus the flame will be stable, and vice versa. Fig 4(a) illustrates the L_b of diluted syngas - air flames at P_u = 0.1 MPa for Φ = 1.4. L_b of He-diluted syngas - air flame almost keeps the same value. Meanwhile, the additions of CO_2 and N_2 diluents cause L_b to decrease, hence make the flame more sensitive to

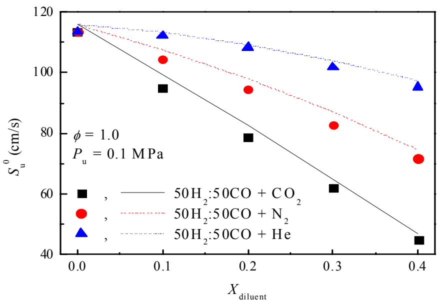

Fig. 3. Measured and predicted S_u^0 of diluted syngas - air flames for Φ = 1.0 at P_u = 0.1 MPa.

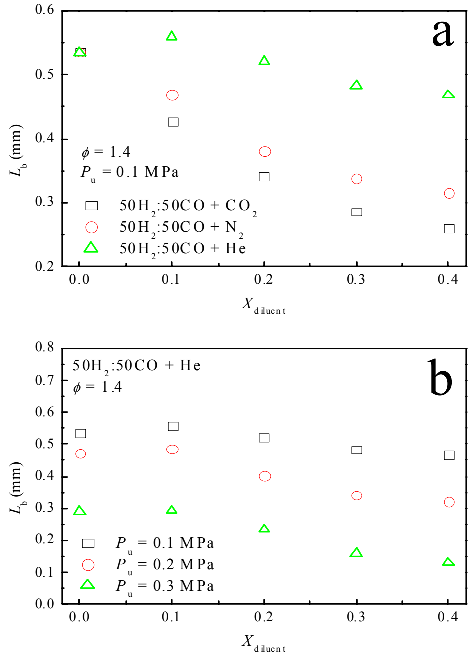

Fig. 4. Markstein lengths of (a) diluted syngas - air flames for Φ = 1.4 at P_u = 0.1 MPa; (b) He-diluted syngas - air flames for Φ = 0.8 at various P_u.

flame stretch effects. Fig 4(b) shows the L_b of He-diluted syngas - air flames for Φ = 1.4 at various initial pressure. L_b decreases with the increase of P_u, thus the flame instability becomes more susceptible with the increase of P_u.

3.2. Flame morphology

Fig. 5 illustrates that the flame fronts remain a smooth surface at P_u = 0.1 MPa, while the

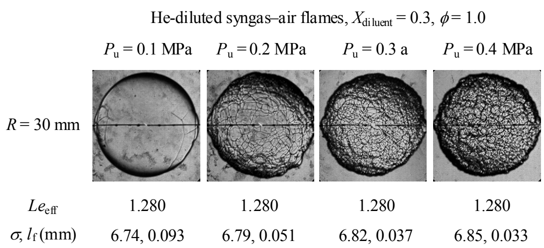

Fig. 5. Schlieren pictures of He-diluted syngas - air flames for Φ = 1.0 and $X_{diluent}$ = 0.3 at P_u = 0.1, 0.2, 0.3, 0.4 MPa.

flames become more wrinkled as P_u increases. With the increase of P_u, the Le_{eff} keeps the same value, the propensity to destabilize the flame was not affected by the diffusive-thermal effect. The cellular instabilities should be enhanced because of the promotion of the hydrodynamic instability due to the significant decrease of l_f whereas σ almost keeps the same value.

For CO_2 diluent, Fig. 6(a) illustrates that there are no differences in the sequences of the flame front surfaces between the syngas–air flame and the CO_2-diluted syngas–air flames. As the contents of CO_2 diluent in the fuel blends increase, the Le_{eff} decreases, thus the diffusional-thermal instability would be promoted. Meanwhile, the hydrodynamic instability would be diminished because σ decreases and l_f increases significantly. Thus the net effects of the two instabilities can be negligible. Fig 6(b) shows the schlieren images of N_2-diluted syngas–air flames at various dilution ratios. The flame front instabilities were also not diminished when the N_2 dilution ratio in the reactant mixtures increase. Because Le_{eff} changes very small, σ and l_f vary a little. Hence the combined influences of the three parameters make a little variation in flame front instability. For He diluent, Fig. 6(c) shows that the propensity of stabilization tends to be progressively promoted with the increase of He diluent content in the reactant mixture. Note that σ decreases a little and l_f increases a little in increase of He dilution ratio. This will promote the propensity a little to stabilize the hydrodynamic instability. And Le_{eff} of the flame increases with the increase of the He dilution ratio, hence modulates the formation of diffusional-thermal cells. Both the hydrodynamic instability and diffusional-thermal instability are diminished when the content of He diluent in the reactant mixture increases.

Figure 7 shows the reciprocal comparison for the suppressions on cellular instabilities in syngas–air flames and CO_2-, N_2-, He-diluted syngas–air flames at same dilution ratio ($X_{diluent}$ = 0.4) for Φ = 1.4, P_u = 0.3 MPa. A similar behavior of flame front instabilities was observed for syngas–air flames and CO_2-, N_2-diluted syngas–air flames. Meanwhile the wrinkles were not formed for He-diluted syngas–air flames, only some large

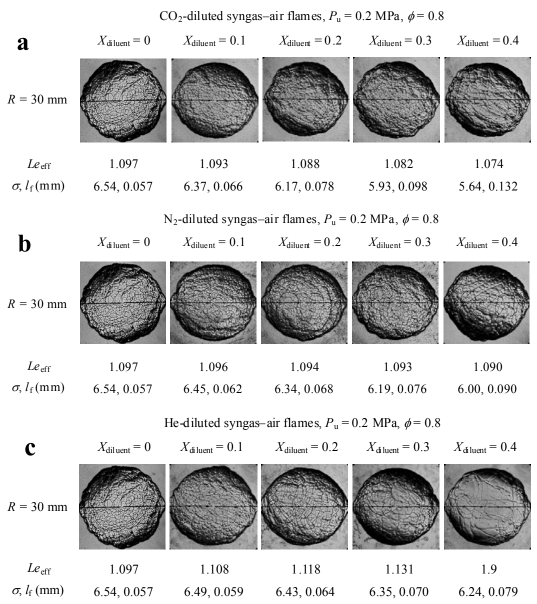

Fig. 6. Schlieren pictures of (a) CO_2– (b) N_2– (c) He–diluted syngas–air flames for overall equivalence ratio of 0.8 at P_u = 0.2 MPa.

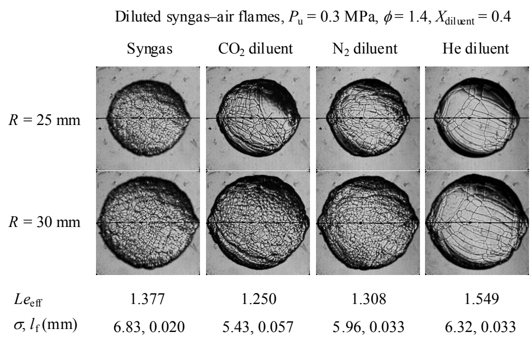

Fig. 7. Schlieren pictures of syngas–air flames with and without dilution for overall equivalence ratio of 1.4 at P_u = 0.3 MPa.

cracks were observed. As tabulated at the bottom of the figure, σ of diluted syngas - air flames decrease and l_f of diluted syngas - air flames increase compared to those of syngas - air flames. Therefore, the effect of hydrodynamic instability in diluted syngas - air flames can be diminished. But for the CO_2- and N_2-diluted syngas - air flames, the effect of diffusional-thermal instability is promoted because of the decrease of the effective Lewis numbers. As a result the combination of the two effects makes the CO_2- and N_2-diluted syngas - air flames have similar behavior with the syngas - air flame. Only the He-diluted syngas - air flames can be modulated the diffusional-thermal instability due to the significant increase of the effective Lewis number. Therefore it can be concluded that the syngas - air flames can be suppressed by adding He diluent in the fuel blends.

3.3. Critical radius, critical Peclet number and critical pressure

The critical radius was detected at the moment when the burning velocity increased significantly and the linear relationship between the stretched flame velocity and the flame stretch rate lost. R_{cr} was also referred from the sequences of the flame images, when cells appeared uniformly over the entire flame surfaces. Both methods gave similar results. Fig. 8 plots the experimentally measured R_{cr} as a function of dilution ratio for Φ = 0.8 at P_u = 0.3 MPa. R_{cr} significantly increases with increasing the contents of He diluent in the mixtures, while R_{cr} slightly increases with the increase of CO_2 and N_2 diluents. This indicates that the onset of instability will be delayed when increasing He dilution ratio, whereas it nearly keeps similar situation for CO_2- and N_2-diluted cases.

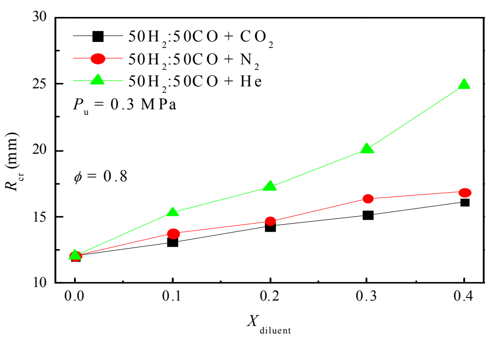

Fig. 8. Measured critical radii for onset of cellular instabilities for Φ = 0.8 at P_u = 0.3 MPa.

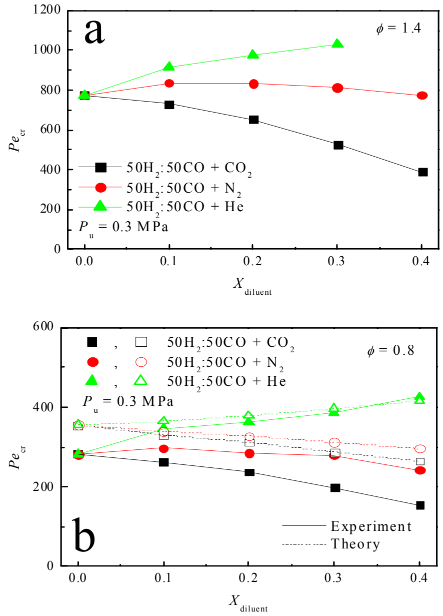

Fig. 9. (a) Experimentally measured Pe_{cr} for Φ = 1.4 at P_u = 0.3 MPa and (b) the comparison between theoretical and experimental Pe_{cr} for Φ = 0.8 at P_u = 0.3 MPa.

Figure 9(a) shows the experimental critical Peclet number, $Pe_{cr} = R_{cr}/l_f$, as a function of dilution ratio, for Φ = 1.4. The Pe_{cr} increases significantly with the increase of He diluent in the fuel blends, it means that the flame front instabilities are delayed to larger radii, hence yielding a larger Pe_{cr}, whereas the Pe_{cr} approximately keep the same values for N_2-diluted syngas - air flames and decrease for CO_2-diluted syngas - air flames. This means the stabilizing effect will become stronger when increasing the He dilution ratio in the fuel blends. The theoretically predicted Pe_{cr} is only applicable to lean mixtures, hence the Pe_{cr} obtained experimentally can be compared with the theoretical ones for Φ= 0.8. The theory and experiment showed the same trend as illustrated in Fig. 9(b), the Pe_{cr} increase with the adding of He diluent in the fuel blends, and decrease a little for N_2-diluted cases and decrease fairly for CO_2-diluted syngas–air flames.

The chamber pressure, at which the flame lost its stability at R_{cr} = 23–25 *mm*, was defined by the critical pressure, P_{cr}. In Fig. 10, P_{cr} in CO_2- and N_2-diluted syngas–air flames increase mildly, whereas P_{cr} in He-diluted syngas–air flames increase significantly in increase of dilution ratios in the reactant mixtures. It means that for the initiation of the cellular instabilities at a similar critical radius, the He-diluted syngas–air flames need higher initial pressures compared to the two other N_2- and CO_2-diluted syngas–air flames.

4. Conclusions

(1) S_u^0 decrease according to increase of dilution ratio in the reactant mixtures. S_u^0 also decrease with the increase of initial pressure.
(2) L_b of He-diluted syngas–air flame almost keeps the same value whereas L_b of CO_2- and N_2-diluted syngas–air flames decrease with the increase of diluent concentrations. L_b also decreases with the increase of initial pressure.
(3) Le_{eff} of He-diluted syngas–air flame always increase whereas Le_{eff} of CO_2- and N_2-diluted syngas–air flames decrease for all cases shown.
(4) Increasing of initial pressure makes the flame more unstable because of the enhancement of hydrodynamic instability due to the significant decrease of the flame thickness.
(5) The similar behavior of cells formation with syngas–air flame is observed when diluted syngas–air mixture with CO_2 and N_2. Meanwhile, for the syngas–air flame with He diluted, the cellular instabilities can be suppressed because of the modulation of both hydrodynamic instability and diffusional-thermal instability.

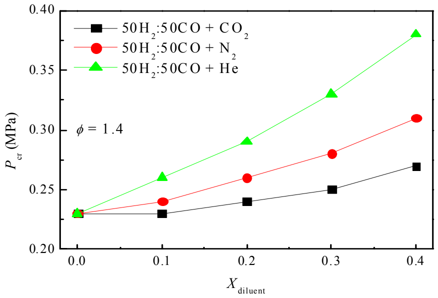

Fig. 10. Critical initial pressures for R_{cr} = 23–25 *mm* of various diluted syngas–air flames.

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