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Measurement of Laminar Burning Velocities of Dimethyl Ether−Air Premixed Mixtures with N_2 and CO_2 Dilution

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Measurements of laminar burning velocities of dimethyl ether−air premixed mixtures with N_2 and CO_2 dilution were made at room temperature and atmospheric pressure using the spherically expanding flame and schlieren photography over a wide range of dilution and equivalence ratios. The stretched flame propagation speed, the unstretched flame propagation speed, the unstretched laminar burning velocity, and the Markstein length (L_b) were obtained and analyzed. The results show that the flame speeds and the burning velocities decrease monotonously with the increase of the dilution ratio. The maximum value of the unstretched laminar burning velocity is presented at the equivalence ratio of 1.1, regardless of N_2 dilution ratios, while it slightly shifts to the rich mixture side with the increase of the CO_2 dilution ratio. This phenomenon reveals the different dilution effect on the unstretched laminar burning velocity between the triatomic molecule gas CO_2 and the diatomic molecule gas N_2. The Markstein length increases with the increase of the dilution ratio. The addition of diluents to the stoichiometric and/or the lean mixture has a larger influence on the Markstein length compared to those of the rich mixture. The addition of diluents obviously enhances the stability of the flame front for the lean mixture, but the impact is slight for the rich mixture. The influence of CO_2 as the diluent on the flame speed and the flame stability is larger than that of N_2 as the diluent for dimethyl ether−air mixture combustion.

1. Introduction

To solve the problems of energy shortage and environmental pollution, research on clean alternative fuels and high-efficient low-emission internal-combustion engines has been carried out around the world. As an alternative fuel, dimethyl ether (DME) receives considerable attention. DME is the simplest aliphatic ether, which has no carbon−carbon bonds (low sooting potential), high cetane number of 55−60, low boiling point at atmospheric pressure, and high oxygen content (34.8% by weight).[1] These fuel properties facilitate clean combustion (i.e., no smoke emission) and better fuel auto-ignition. However, because of the high oxygen content of DME, the NO_x emission is the major problem to be solved in DME combustion and engine operation. Mixture dilution and/or exhaust gas recirculation (EGR), which has been widely used in both the spark- and compression-ignition engines,[2,3] are regarded as effective methods in reducing the combustion temperature and NO_x emission. With high oxygen content, DME has a higher tolerance to EGR than that of diesel fuel. Previous work in engines revealed the simultaneous reduction of particulate matter and NO_x when operating the DME engine combined with EGR while maintaining low emissions of CO and unburned hydrocarbons.[3−6]

The fundamental characteristics of a mixture, such as laminar burning velocity and Markstein length (indicating flame instability), are theoretically important in validating the chemical reaction mechanism and practically important for engine system design and optimization. Some investigators used the different methods to measure the burning velocity of DME. Daly measured the burning velocities of the DME−air mixture by means of spherically expanding flames.[7] Gibbs studied the burning velocities of DME with a Bunsen burner.[8] Kaiser studied the premixed DME−air flames at atmospheric pressure by an experimental and modeling method.[9] Huang et al. studied the burning velocity and combustion characteristics of the DME−air mixture with the spherically expanding flames.[10] Qin obtained the burning velocities of DME−air premixed flames

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at elevated pressures.[11] However, few reports are found on the burning velocities and combustion characteristics of the DME−air−diluent mixture.

The objective of this paper is to measure the laminar flame propagation speeds, the laminar burning velocities, and the Markstein lengths of DME−air−diluent premixed mixtures at various equivalence ratios and dilution ratios by using high-speed schlieren photography. The effects of CO_2/N_2 dilution on burning velocities and the Markstein lengths are studied.

2. Experimental Setup and Method

In this study, the dilution ratio is defined as the volumetric fraction of diluent addition in the mixtures [$\phi_r = V_{diluent}/(V_{fuel} + V_{air} + V_{diluent})$]. The experiments were conducted in a cylindrical constant volume vessel (diameter of 130 mm and length of 130 mm). Two sides of the vessel are mounted with the quartz windows to allow for optical access. A HG-100 high-speed digital camera operating at 10 000 frames/s was used to record the flame pictures during the flame propagation. The mixtures were prepared by introducing each component to its corresponding partial pressure, which were measured by the U-tube mercury manometer, according to the specified equivalence ratio and dilution ratio. Experiments were conducted at the initial pressure of 0.097 MPa and the initial temperature of 293 K. DME is in the gaseous state at room temperature and pressures less than 0.5 MPa; thus, the homogeneous DME−air−diluent mixture can be prepared in the vessel. To avoid the influence of the wall temperature on the mixture temperature, there was a sufficient interval between two experiments, and this can provide enough time for the wall to cool and maintain the initial temperature. The mixtures were ignited by centrally located electrodes, and a standard capacitive discharge ignition system was used for producing the spark. In this study, the ignition energy was 45 mJ. The pressure was recorded by a Kistler absolute pressure transducer with a resolution of 0.01 kPa.

The initial and partial pressures of each component were measured with a U-tube mercury manometer, with a measuring accuracy of 66 Pa. The authors determined the inaccuracy of the equivalence ratio using the propagation of errors formulas. The biggest error of the equivalence ratio is 1.879% ($\phi = 0.8$, 0.05 N_2/CO_2). For mixtures without dilution, the authors repeated the experiment 3 times and found for most conditions that the 3 results were coincident with each other. In addition, for several conditions, the results are not so identical; we repeated the experiment for another 2 times and chose the average of the mostly approach ones or the middle one as the result.

For the spherically expanding flame, the stretched flame velocity, S_n, reflecting the flame propagating speed, is derived from the flame radius versus time[12,13]

$$S_n = \frac{dr_u}{dt} \tag{1}$$

where r_u is the radius of the flame and t is the elapsed time from spark ignition; thus, S_n can be directly obtained from flame photos in schlieren photography.

the flame stretch rate, α, represented the expanding rate of the flame front area. In a quiescent mixture, it is defined as

$$\alpha = \frac{d(\ln A)}{dt} = \frac{1}{A}\frac{dA}{dt} \tag{2}$$

(11) Qin, X.; Ju, Y. G. Measurements of burning velocities of dimethyl ether and air premixed flames at elevated pressures. *Proc. Combust. Inst.* **2005**, *30* (1), 233–240.

(12) Bradley, D.; Gaskell, P. H.; Gu, X. J. Burning velocities, Markstein lengths, and flame quenching for spherical methane−air flames: A computational study. *Combust. Flame* **1996**, *104* (1−2), 176–198.

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where A is the area of any infinitesimal element of the flame surface. For the spherically outwardly expanding flame front, the flame stretch rate can be simplified as

$$\alpha = \frac{1}{A}\frac{dA}{dt} = \frac{2}{r_u}\frac{dr_u}{dt} = \frac{2}{r_u}S_n \tag{3}$$

With respect to the early stage of flame expansion, there exists a linear relationship between the flame speeds and the flame stretch rates;[14] that is

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

where S_l is the unstretched flame propagation speed, which can be obtained as the intercept value at $\alpha = 0$, in the plot of S_n versus α. The burned gas Markstein length L_b is the negative value of the slope of the S_n−α curve. The diffusional-thermal instability of the flame front is dependent upon the Markstein length L_b. Positive values of L_b, which correspond to Lewis numbers larger than unity, and the flame speed decrease with the increase of the flame stretch rate. If any kind of protuberance appears at the flame front (stretch increasing), the flame speed at the flame protruding position will be suppressed, and this makes the flame stable. In contrast to this, negative values of L_b correspond to a Lewis number smaller than unity, indicating that the flame speed increases with the increase of the flame stretch rate; in this case, if any kind of protuberance appears at the flame front, the flame speed at the flame protruding position will be increased, and this decreases the flame front stability.[11,15]

The characteristics of the igniter can influence the measured value of the burning velocity. A previous study showed that the flame speeds were independent of the ignition energy when the flame radius is larger than 5 mm.[10] Together with the consideration of the isobaric combustion, the data reduction is limited within the flame radius ranging from 5 to 25 mm (the pressure rise rate is within 1.0%).

When the observation is limited to the initial part of the flame expansion, where the pressure varies little, a simple relationship linking the flame propagation velocity S_l to the unstretched laminar burning velocity u_l is given as follows:

$$u_l = \rho_b S_l/\rho_u \tag{5}$$

where ρ_b and ρ_u are the densities of the burned and unburned gases, respectively. ρ_u can be obtained according to the initial state, and ρ_b is determined from thermal equilibrium calculation.

Because of the finite thickness, there exist two possible definitions for the stretched laminar burning velocity depending upon whether the burning velocity is defined at the unburned gas side or burned gas side. These two burning velocities are the stretched laminar burning velocity u_n, which is the burning velocity related to the entrainment of the unburned gas, and the stretched mass burning velocity u_{nr}, which is the burning velocity related to the production of the burned gas, proposed by Bradley[12] and calculated by

$$u_n = S\left[S_n\frac{\rho_b}{\rho_u}\right] \tag{6}$$

$$u_{nr} = \frac{\rho_b}{\rho_b - \rho_u}(u_n - S_n) \tag{7}$$

where S is a function that depends upon the flame radius and the density ratio. It accounts for the effect of the flame thickness on the mean density of the burned gases. The expression of S in the study used the formula given by Bradley et al.[12,16]

$$S = 1 + 1.2\left[\frac{\delta_l}{r_u}\left(\frac{\rho_u}{\rho_b}\right)^{2.2}\right] - 0.15\left[\frac{\delta_l}{r_u}\left(\frac{\rho_u}{\rho_b}\right)^{2.2}\right]^2 \tag{8}$$

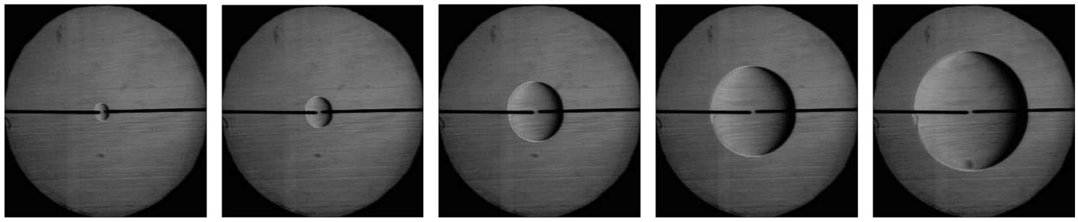

Figure 1. Schlieren photographs of DME−air−CO_2 mixtures.

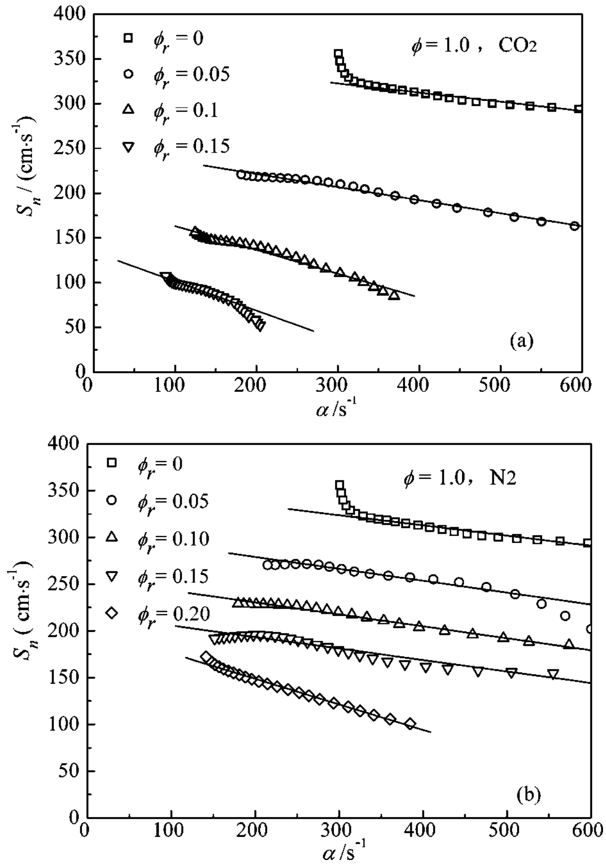

Figure 2. Stretched flame propagation speed versus stretch rate at different dilution ratios.

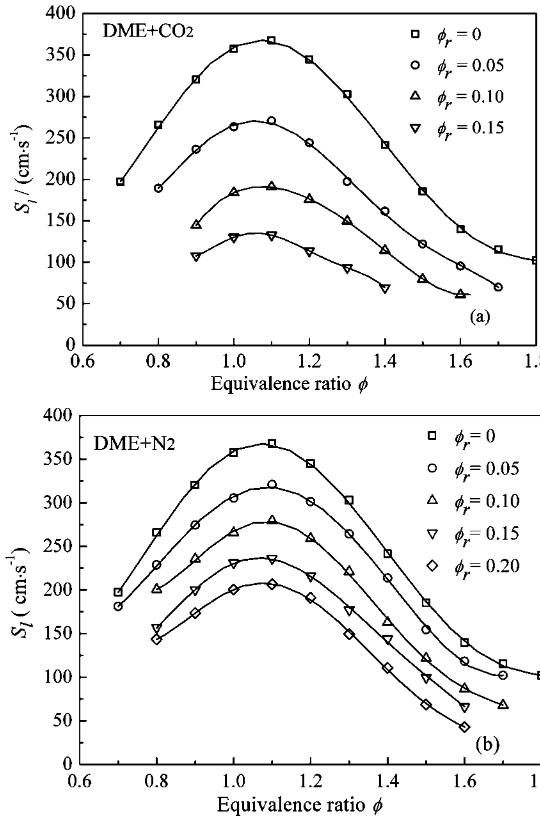

Figure 3. Unstretched flame propagation speed versus equivalence ratio at different dilution ratios.

Here, δ_l is laminar flame thickness given by $\delta_l = \nu/u_l$, where ν is the kinematic viscosity of unburned mixture and u_l is the unstretched laminar burning velocity of the flame.

3. Results and Discussion

3.1. Flame Propagation Speed and Markstein Length. Figure 1 shows the schlieren photographs of the DME−air−CO_2 at an equivalence ratio of 1.0 and dilution ratio of 10%. In this case, the smooth spherically expanding flame propagates from the chamber center. In fact, nearly all of the schlieren photographs of the DME−air−CO_2/N_2 mixtures in the experiment have smooth flame fronts, just a few of which have cracks when the flame propagates larger than the largest radius demanded in the calculation. Thus, in this paper, the largest radius used in the determination is only restricted by the pressure rise. Meanwhile, at the early stage of flame development, the cooling effect of the electrodes on the flame propagation is observed, and this leads to slow flame propagation along the direction of the electrodes compared to the vertical direction. When the flame radius has developed to a certain value, there is little effect of the electrodes. To avoid the influence from the electrodes, the flame radius used in the calculation uses the radius in the vertical direction.

Figure 2 shows the stretched flame propagation speed (S_n) of the stoichiometric DME−air−N_2/CO_2 mixtures versus the stretch rate at different ϕ_r. We can see that, for both mixtures with either CO_2 or N_2 as the diluent, S_n decreases monotonously with the increase of ϕ_r, and this indicates that the addition of dilution gas can decrease S_n of the mixtures. At any ϕ_r, S_n decreases with the increase of the stretch ratio α. The slopes of the S_n−α curves all take the negative values, corresponding to the positive values of Markstein lengths and the stable tendency of the flame fronts. The study shows that the dilution effect on S_n is larger in the case of CO_2 compared to N_2.

Figure 3 gives the unstretched flame propagation speed (S_l) versus equivalence ratio ϕ at different dilution ratios. For both CO_2 and N_2 dilution, S_l gives its peak value at $\phi = 1.1$ and it

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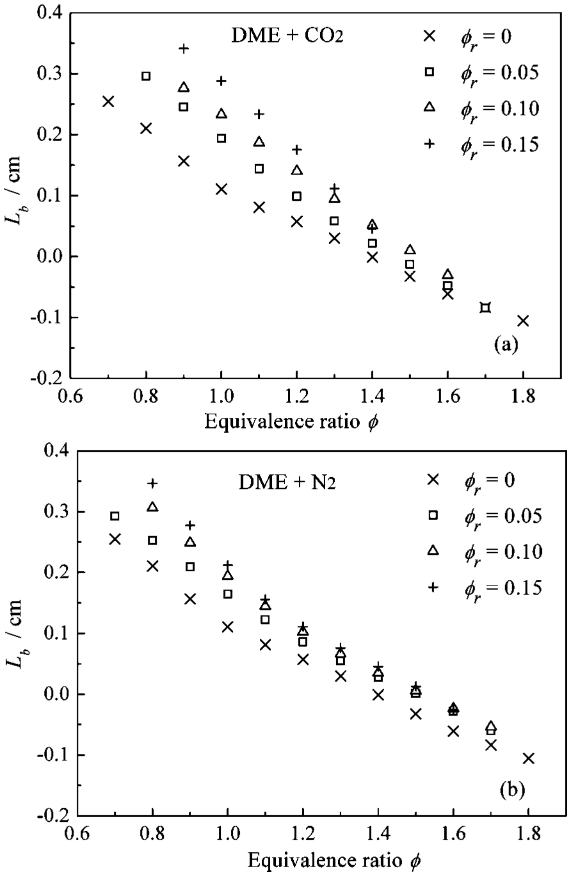

Figure 4. Markstein length versus equivalence ratio at different dilution ratios.

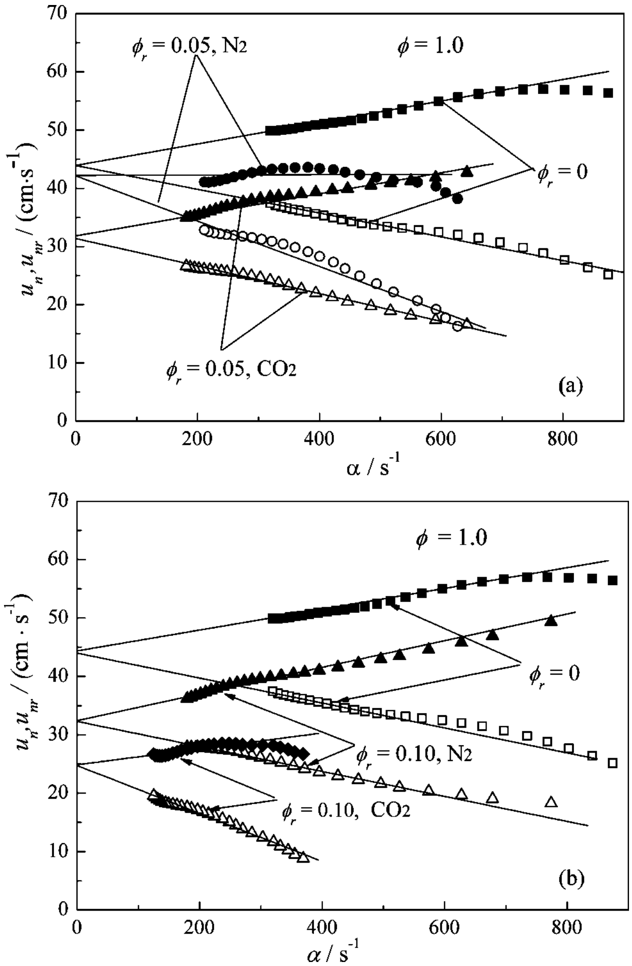

Figure 5. Stretched laminar burning velocity versus stretch rate at different dilution ratios. $\phi = 1.0$; u_n, solid point; u_{nr}, hollow point.

decreases monotonously with the increase of the dilution ratio. CO_2 and N_2 are the inactive gases. The dilution of the DME−air mixtures by these gases decreases the molar fraction of oxygen and fuel, lowering the probability of the fuel molecule to meet with the oxygen molecule. Moreover, mixture dilution decreases the temperature of the flame by increasing the specific heat of the mixture. These two factors decrease the chemical reaction rate and, furthermore, the flame speed.

Under a specific dilution ratio, the unstretched flame propagation speed with CO_2 dilution gives a lower value than that with N_2 dilution. The specific heat ratio of triatomic molecule gas CO_2 is higher than that of diatomic molecule gas N_2; thus, CO_2 will absorb the released heat more and result in a larger drop of the temperature within the reaction zone of flames compared to N_2.

At the initial stage of the flame propagation, the Markstein length (L_b) can be used to reflect the sensitivity of the flame stretch rate and the stability of the flame front.[12] A large value of the Markstein length reflects a high stability of the flame front.[7,12] As shown in Figure 4, the Markstein length increases with the increase of the dilution ratio, and this reveals that the mixture dilution can increase the stability of the flame front. The Markstein length at $\phi = 1.0$ and/or lean mixture ($\phi < 1.0$) gives the higher values by mixture dilution compared to those at the rich mixture side, and the increment becomes smaller in the case of $\phi > 1.2$. This indicates that adding diluents can effectively improve the stability of the flame front for the lean mixture but slightly improves the stability of the flame front for the rich mixture. The Markstein length decreases with the increase of the equivalence ratio for the DME−air−CO_2/N_2 mixtures, and this suggests that the flame front of the lean mixture maintains the higher stability compared to the rich mixture.

3.2. Laminar Burning Velocity. Figure 5 shows the stretched laminar burning velocity (u_n) and the stretched mass burning velocity (u_{nr}) versus the stretch rate for the stoichiometric mixture at $\phi_r = 0.05$ and 0.10. The difference between u_n and u_{nr} is clearly demonstrated. u_n denotes the rate of mixture entrainment and usually increases as the stretch rate increases. In contrast, u_{nr} is the burning velocity related to the production of burned gas and usually decreases as the stretch rate increases. The difference between the stretched laminar velocity and the stretched mass burning velocity, $u_n - u_{nr}$, increases with the increase of the stretch rate, and this is due to the influence of flame thickness on the burning velocities. A large value of $u_n - u_{nr}$ is presented at small radii (corresponding to a high stretch rate), where the flame thickness (δ_l) is the same order as the flame radius. As the definition indicated, a high value of the stretch rate corresponds to the small flame radius; thus, the influence by δ_l becomes large. When the stretch rate reaches zero, the flame radius becomes infinity and the influence of δ_l can be negligible. Thus, u_n and u_{nr} will obtain the same value; that is, both u_n and u_{nr} will reach the unstretched laminar burning velocity u_l. For a specific ϕ_r, the value of $u_n - u_{nr}$ with CO_2 as the diluent gives a larger value than that with N_2 as the diluent, and this indicates that δ_l has the larger influence on the burning velocity with CO_2 dilution compared to that with N_2 dilution.

Figure 6 shows the unstretched laminar burning velocity (u_l) of the diluted mixtures versus the equivalence ratio at different

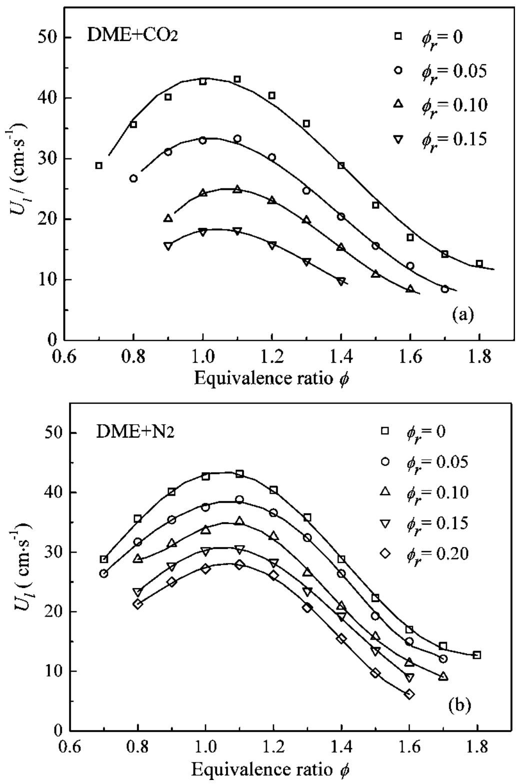

Figure 6. Unstretched laminar burning velocity versus equivalence ratios at different dilution ratios.

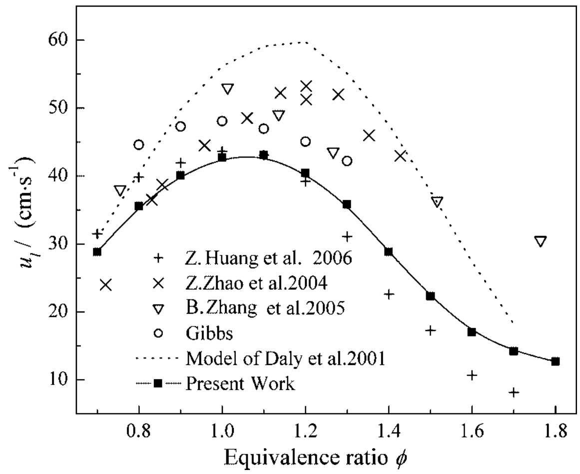

Figure 7. Unstretched laminar burning velocity versus equivalence ratio.

dilution ratios. For both CO_2 and N_2 dilution, u_l decreases monotonously with the increase of the dilution ratio ϕ_r. The maximum value of u_l is presented at the equivalence ratio of 1.1 regardless of N_2 dilution ratios, while it slightly shifts to the rich side with the increase of the CO_2 dilution ratio. This phenomenon reveals the different dilution effect on u_l between the triatomic molecule gas CO_2 and the diatomic molecule gas N_2. Moreover, radiation of CO_2 is larger than N_2. Mixture dilution by CO_2 gives the larger reduction in u_l compared to N_2. This is consistent with the behavior of S_n and S_l diluted by the two inert gases.

Figure 7 gives the comparisons of the present study to the previous literature.[7,8,10,17,18] The present study and ref 10 use the spherically expanding flame but differ in vessel geometry (cylinder-type vessel in the present study and cubic-type vessel in ref 10) and experimental condition (initial pressure of 0.097 MPa and initial temperature of 293 K in the present study and initial pressure of 0.096 MPa and initial temperature of 283 K in ref 10). They give the most approximate value in u_l. The difference in u_l between the present study and other literature is due to the different methods in measuring the flame speed. Zhang et al. used the counterflow double-flame method,[18] and Zhao et al. used the single jet-wall stagnation flame method[17] to measure the burning velocity of DME−air flames; because of the presence of the negative stretching in the flame, the stretched laminar burning velocity increases with the increase of the stretch rate. However, the spherically expanding flame in the constant volume chamber has the characteristics of positive stretching in the flame, and the stretched laminar burning velocity decreases with the increase of the stretch rate. Both the work by Daly et al.[7] and Zhao et al.[17] also revealed that u_l obtained by a spherically expanding flame gave a lower value compared to those determined by the counterflow double-flame method and jet-wall stagnation flame method.

4. Conclusions

Measurements of laminar burning velocities of DME−air premixed mixtures with N_2 and CO_2 dilution were studied using the spherically expanding flame at different dilution ratios and equivalence ratios. The main results are summarized as follow: (1) The flame speeds and the burning velocities decrease monotonously with the increase of the dilution ratio. The maximum value of u_l is presented at an equivalence ratio of 1.1 regardless of N_2 dilution ratios, while it slightly shifts to the rich side with the increase of the CO_2 dilution ratio. (2) The Markstein length increases with the increase of the dilution ratio. The addition of diluents to the stoichiometric and/or the lean mixture has a larger influence on the Markstein length compared to those to the rich mixture. The addition of diluents obviously enhances the stability of the flame front for the lean mixture, but the impact is slight for the rich mixture. (3) The influence of CO_2 as the diluent on the flame speed and the flame stability is larger than that of N_2 as the diluent for DME−air mixture combustion.

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