# Measurement of Laminar Buring Velocity, Markstein length, and Cellular Instability of Dimethyl Ether and Syngas-added Dimethyl Ether-Air Premixed Spherical Flames

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## 1 Introduction

Environmental regulations and the unbalance of energy supply and demand have proven the necessity of alternative or renewable energies. One of acceptable alternative fuels is dimethyl ether ($CH_3OCH_3$, DME) due to its considerable merits such as the low emission of combustion product, the low boiling temperature (about 25℃), and the high cetane number (55-60). In these regards, many researches have been conducted with DME to develop production methods based on the high efficiency [1] as well as to investigate fundamental combustion characteristics [2, 3] and chemical reaction mechanisms [4]. Clearly, it is necessary to reduce the combustion emission and enhance the system efficiency at the same time. Though it is the best alternative to add the hydrogen into the combustible mixture in the side of extending flammable limit, it has a problem with safety and economic reasons [5]. Thus, the syngas, which typically consists of hydrogen and carbon monoxide, is regarded as a solution because it is formed from a variety of resources such as coal, biomass, refinery residual, etc. [6, 7], and is less dangerous than hydrogen. Furthermore, advantages in syngas-enriched flames are fully expected with respect to the extension of flammability limit and the reduction of pollutant emissions like $CO_2$ in lean combustion [7]. On the basis of these significant anticipations in both dimethyl ether and syngas, the present study in outwardly propagating spherical flame was conducted with the multi-component fuel blend of DME and syngas to investigate the unstretched laminar flame speed, the Markstein length, and the cellular instability by adding 25%, 50%, and 75% syngas with the fixed composition of 50%$H_2$ and 50%CO into DME-air mixtures at room temperature and elevated initial pressure. The measured laminar burning velocity was compared with that of numerical analysis calculated by PREMIX [8] code with Zhao reaction mechanism [4], and flame instability was evaluated through Markstein length and cellular instability.

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## 2 Experimental facility

The experiments were conducted in a stainless steel, cylindrical constant volume chamber having an inside diameter of 200 mm and a length of 220 mm. Optical access was provided by quartz windows (two 100-mm-diameter and 40-mm-thickness) mounted in the side of longitudinal direction of the chamber as shown in Fig. 1. Two tungsten electrodes having diameters of 0.5 mm were linked to a high voltage source (varied from 8 to 10 kV) to ignite combustible mixture at the centre of the chamber. Fuels and air were supplied inside the chamber at corresponding partial pressures using the absolute pressure transmitter (AEP LabDMM, -1-40 bar, ±0.05% FSO) to attain the total initial chamber pressure, $P_u$. A time interval of 15 min was awaited to ensure the complete mixing and attainment of a quiescent condition. Once the voltage source was given, a flame kernel formed at the centre of the chamber, started propagating outward spherically and quenched when it touched the walls of the chamber. The propagating spherical flame was visualized using schlieren photography with a 300-W xenon light source and a pair of 150-mm-diameter spherical concave mirrors and recorded using a high-speed digital camera (Olympus i-SPEED 3) with the shutter time of 10,000 fps. The signal of spark source, recorded high-speed images, and the instantaneous pressure signal were triggered. Temporal chamber pressure during combustion was monitored by a pressure transducer (Kistler 601A, 0-250 bar, ±0.5% FSO) and a data logger (GRAPHTEC GL900). After combustion, the chamber was vented to the laboratory exhaust system and then purged using an air compressor to remove condensed water vapor prior to refilling for the next experiment.

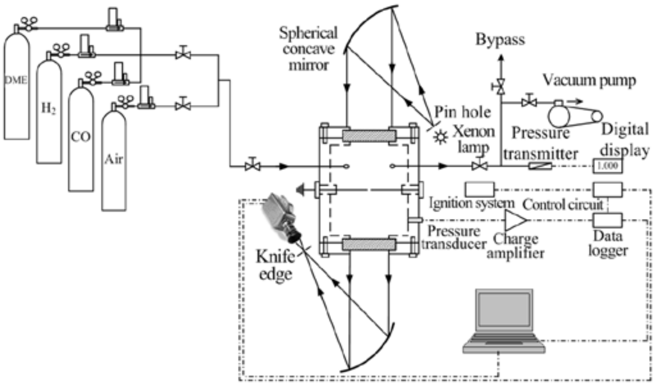

Figure 1 Schematic representation of the experimental setup.

## 3 Results and discussion

Fig. 2 shows the dependency of the burned gas Markstein length ($L_b$) on the equivalence ratio at $P_u$ = 0.1 MPa and $T_u = 298 \pm 3\ K$ in syngas-added DME-air premixed flames. Totally, the Markstein length decreased with the increase of the equivalence ratio. Exceptionally, the Markstein length in 75% syngas-added DME flame increased from equivalence ratio 0.6 to 1.0 and then maintained almost constant value of $L_b$, passing by that of 1.0. This tendency was rather in agreement with those of syngas flame with the composition of 50% $H_2$ + 50% CO conducted by Prathap et al. [6] because the majority of fuel component in the mixture is syngas. In the fuel-lean regime, it was clear that the Markstein length decreased in increase of the syngas fraction because the Lewis number of DME and hydrogen are larger and smaller than unity at fuel-lean regime, respectively, remaining $Le_{CO} \sim 1$ at both fuel-lean and -rich conditions. In the fuel-rich regime, on the other hand, the dependency of the Markstein lengths occurred conversely because of high content of hydrogen which is Lewis number larger than unity at fuel rich regime.

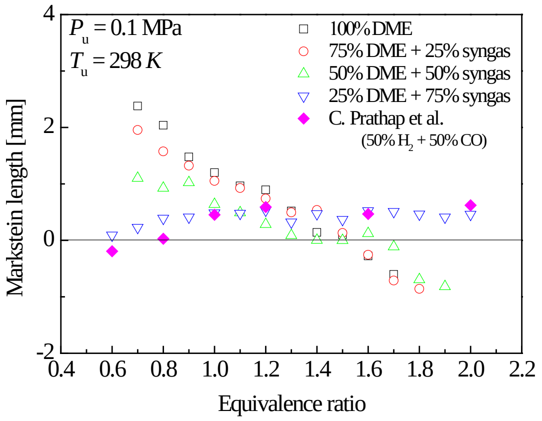

Figure 2 The effect of syngas addition on the Markstein length in DME-air premixed flames; $P_u$ = 0.1 MPa and $T_u$ = 298 ± 3 $K$.

It is well known that the GRI-Mech 3.0 mechanism is the best fitted for representing characteristics of methane-air flame. Thus, it is important to verify both the experimental skill and the data treatment method by comparing the results of methane-air flames on unstretched laminar burning velocities between measurements and predictions. The figure in the left side of the fig. 3 shows the comparison of the unstretched laminar burning velocities of $CH_4$-air flames among the present experiment, predicted by GRI-Mech 3.0, and performed by other research groups. It is clear that results of the present study are in agreement with those of predicted and measured by other groups. The measured in the same way, the dependency of the present unstretched laminar burning velocities upon the equivalence ratio with existing reliable experimental results in pure DME-air premixed flames are indicated in right side of the fig. 3. The data of Huang et al. [9] and Chen et al. [10] were over-estimated in the lean side and under-estimated in the rich side. Those of Daly et al. [3] were under-estimated in the rich side. The present experimental results were in agreement with those of Qin and Ju [2].

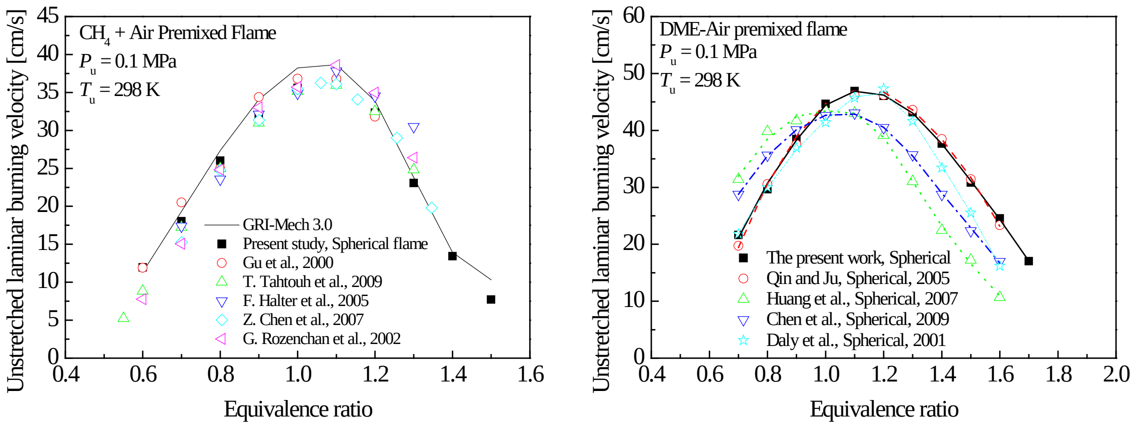

Figure 3 Unstretched laminar burning velocities measured at $P_u$ = 0.1 MPa and $T_u$ = 298 ± 3 $K$ in $CH_4$-air (left) and DME-air (right) premixed flames.

Fig. 4 represents effects of syngas addition on unstretched laminar burning velocities measured and calculated by Zhao model [4] in DME-air premixed flames. Except for 75% syngas added DME-air flames, experimental results are lower than those of Zhao model in the equivalence ratio less than 1.4 whereas that of larger than 1.4, results of Zhao model are higher than those of experiments. The maximum burning velocities were found at equivalence ratio of 1.1 for 0%, 25%, and 50% syngas added DME-air flames but it was shifted to 1.2 for 75% syngas added DME-air flame. And the burning velocities increased significantly as syngas is added in DME-air mixtures. It has been well known that the peak burning velocity of DME and syngas (50% $H_2$ + 50% CO) are at equivalence ratio 1.1 and 2.0, respectively. Therefore, all ranges of the peak burning velocity for DME-syngas-air flames should be between equivalence ratio 1.1 and 2.0. In this sense, until 50% syngas-added DME-air flames have less effective in syngas addition. While, 75% syngas-added DME-air flame, DME-air flame was affected by syngas.

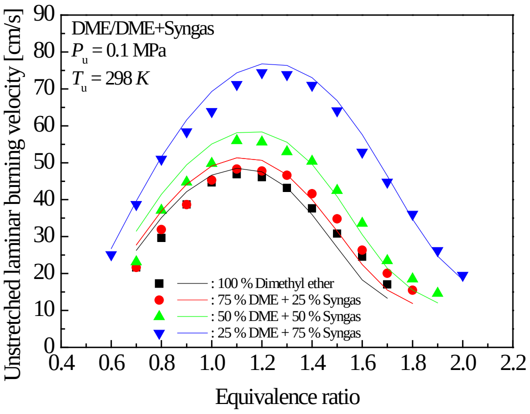

Figure 4 Measured (symbol) and predicted (line) unstretched laminar burning velocities in DME/DME+Syngas flames at $P_u$ = 0.1 MPa and $T_u$ = 298 ± 3 *K*.

Fig. 5(a) and (b) illustrate the schlieren images of the flame sequences with the increase of the syngas fraction in DME-air mixtures for overall equivalence ratio of 0.8 at $P_u$ = 0.2 MPa and 0.3 MPa, respectively. To be affected by buoyancy instability, the flame speed should be slower than 16.27 cm/s in this study. However, because the minimum burning velocity found in fig. 5 was 21.46 cm/s ($X_{syngas}$ = 0 at $P_u$ = 0.3 MPa) only hydrodynamic (thermal expansion ratio, $\sigma$, and flame thickness, $l_f$) and diffusional-thermal instabilities (effective Lewis number or deficient reactant Lewis number) were calculated to evaluate cellular instability. The thermal expansion ratio and the flame thickness were calculated by $\sigma = \rho_u / \rho_b$ and $l_f = (\lambda / c_P)/(\rho_u S_u^0)$, respectively. Here, $\lambda$ and $c_P$ respectively are the thermal conductivity and the specific heat at 1200 K, which is approximately the average of the freestream and flame temperatures. [7] Note that the first columns in both figures, mixtures contain single fuel (i.e. dimethyl ether) thereby the deficient reactant Lewis number was used. The Lewis number, the thermal expansion ratio, and the flame thickness are indicated at the bottom of the figures. Nevertheless, the propensity of Lewis number decreased in increase of syngas fraction, there is no occurrence of instability in terms of diffusional-thermal since all of Lewis numbers calculated is larger than unity. Meanwhile, there appeared many cells over the entire flame surface in higher syngas-added DME-air flames. As syngas was added in DME-air mixtures, both the thermal expansion ratio and flame thickness were decreased. The decreased tendency in thermal expansion ratio means that it suppresses the hydrodynamic instability. In figs. 5(a) and (b), however, there are wrinkled more in higher syngas fraction. Therefore, the effects of reduced flame thickness caused hydrodynamic instability rather than the density gradient at the ignition stage because both thermal expansion ratio and flame thickness decrease as syngas is added in DME-air mixtures. Additionally, in the comparison between figs. 5(a) and (b), the independent variable is the initial pressure. The cells appeared much more in higher initial pressure as shown in these figures. Even though the initial pressure in increased, there is little variation in Lewis number. Meanwhile, the thermal expansion ratio and the flame thickness were increased and decreased, respectively, in the higher initial pressure. As a result, the hydrodynamic instability, in particular the effect of decreased flame thickness, was promoted the cellular instability in high initial pressure.

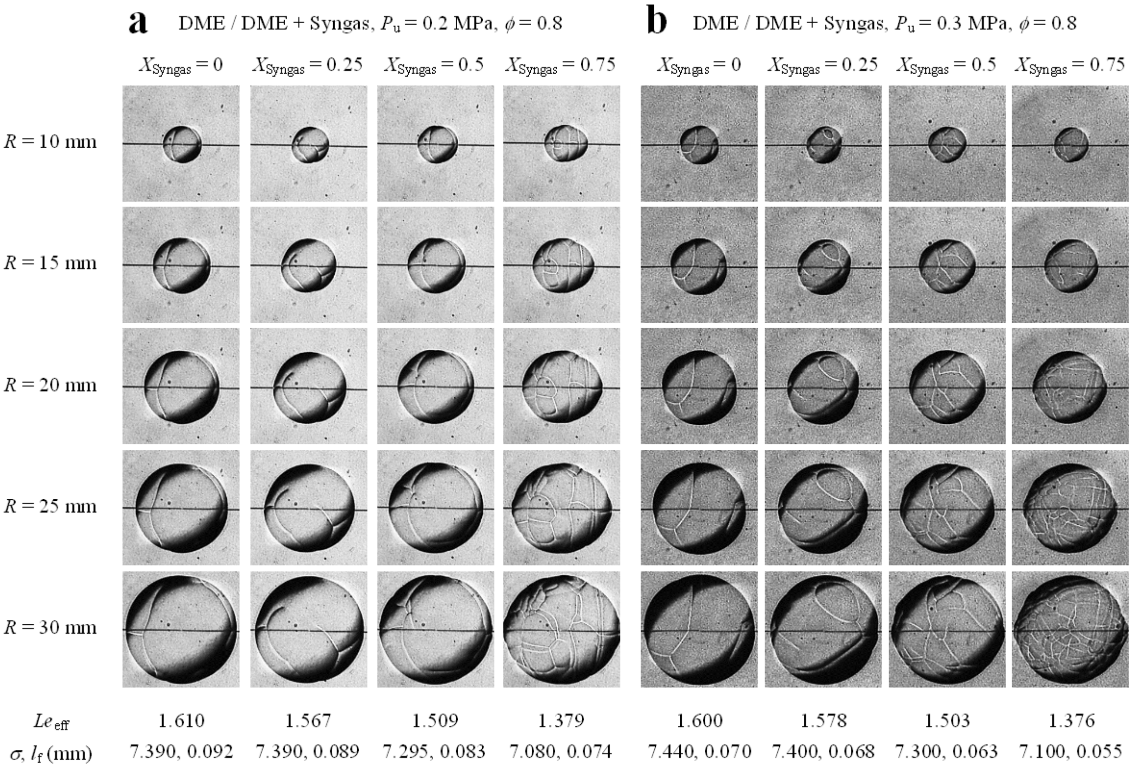

Figure 5 Syngas effects on cellular instability of DME-air premixed flames at $P_u$ = 0.2 MPa (a), 0.3 MPa (b), $T_u$ = 298 ± 3 *K*, and $\phi$ = 0.8.

## 4 Conclusions

The present study was conducted to investigate the Markstein length, unstretched laminar burning velocity, and cellular instability of syngas added (in steps of 25%) DME-air premixed flames and the summary is as follows:

1) The tendency of the burned gas Markstein length was decreased with the increase of the equivalence ratio except for 75% syngas-added DME-air flames due to coupled effects of preferential diffusion of $H_2$ and the unstable combustion characteristics of CO.
2) The maximum burning velocities were found at equivalence ratio of 1.1 for 0%, 25%, and 50% syngas added DME-air flames and 1.2 for 75% syngas added flame.
3) The cellular instability was promoted in higher initial pressure and syngas fraction in the DME-air mixtures, caused by hydrodynamic instability (especially the effect of the decreased flame thickness) for both cases. Also, All the Lewis numbers calculated were larger than unity, it is unnecessary to consider the diffusional-thermal instability for mixtures used in this study.

## 5. Acknowledgement

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