Pressure Effects on Laminar Burning Velocity of SNG/air Mixtures in a Closed Vessel

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1 Introduction

Synthetic natural gas (SNG) is a promising and alternative fuel to natural gas [1,2]. SNG is produced by coal gasification and subsequent methanation processes of synthetic gas at high pressures and temperatures. During its process, CO_2 is pre-captured so coal can be used more cleanly in industrial burners such as gas turbine combustor. SNG mixtures composing of methane, propane, and hydrogen as the main components can have many potential merits, which has the similar lower heating value, lower ignition temperature, and high laminar burning velocity, in comparison with natural gas. Nonetheless, very few studies on the fundamental combustion characteristics for SNG fuel have been reported [3-5].

The one of the basis combustion characteristics, laminar burning velocity is an important factor to understand and control the real combustion phenomenon and enhance accuracy of chemical mechanism at the same time. Markstein length characterizes the variation of combustion velocity related stretch, and it is the essential factor to define the flame instability related to preferential diffusion [6]. In the previous paper [4], it was reported that the laminar burning velocity and Markstein length for SNG fuel experimentally in outwardly propagating spherical premixed flame. It was compared with experimental results and numerically predicted results from GRI-mech 3.0, USC-II, UC San Diego and Aramco 2.0 mechanisms using methane/air mixture for the chamber verification, and suggested Aramco 2.0 mechanism which had the lowest error rate.

In this work, the combustion characteristics of SNG were determined by varying initial pressures and fuel composition ratio, especially hydrogen content, and experiments and numerical analysis were conducted using cylindrical constant volume chamber. To measure laminar burning velocity, the spherically propagating flame is widely used since it is convenient to control the initial pressure, and this method is considered as reliable way for measurement of laminar burning velocity [7].

2 Experiment and Numerical method

The experimental equipment consisted of a cylindrical constant volume combustion chamber (200 mm in diameter and 220 mm in length), an ignition system, and a Schlieren visualization system, as shown

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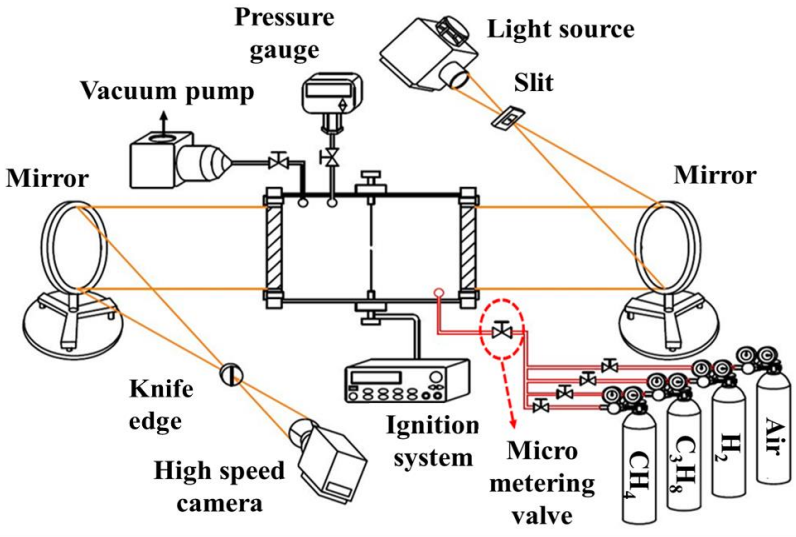

Figure 1: Schematic of experimental setup.

schematically in Fig. 1. Two quartz windows (150 mm in diameter and 45 mm in thickness) were installed for optical access.

The flowrates of fuel and air were adjusted by considering the partial pressures measured with a pressure gauge (AEP Lab DMM, 1 ~ 20 bar, accuracy). Sharp ended two tungsten electrodes with 2mm in diameter were connected to a high voltage source (18 kV) to ignite the mixtures at the center of the chamber. The gap between the electrodes was fixed to 0.7 mm. To ensure the complete mixing of reactants and their quiescence, the experiment was conducted15 minutes after filling. After flame propagation, the products in the chamber were ventilated and purged with compressed air to eliminate condensed water for the next experiment.

Outwardly propagating spherical flames were visualized by a highspeed camera (Photron Inc., FASTCAM 1024 × 1024 pixel) using a Schlieren imaging with a 100 W halogen lamp and a pair of concave mirrors (diameter: 150 mm). The position of the flame front was determined by converting to a monochromatic image via accommodating the IMADJUST function in MATLAB software for image enhancement. Throughout this process, variation of flame radius as function of time was acquired.

Numerical simulation was conducted using PREMIX code[8] at normal temperature and pressure with chemical kinetics, which have been developed to characterize hydrocarbon. Four different chemical kinetics were selected to give the priority via comparing predicted laminar burning velocities with measured data: GRI-mech 3.0[9], ARAMCO 2.0[10], USC-II[11], and UC San Diego[12].

3 Results and discussions

The instantaneous Schlieren images of spherically propagating SNG/air premixed flames at which the upper flame radius reaches 35 mm from the chamber center are presented in Fig. 2 for ϕ = 1.0 at various initial chamber pressures (P_0) up to 0.5 MPa. The SNG flames have smooth flame surfaces at 0.1 and 0.5 MPa, whereas, at P_0 = 0.5 MPa, there are some large-scale cells on the flame surface, especially for ϕ = 1.0. The onset of cellular instability can be defined as the moment when the curve of flame speed versus flame stretch indicates an appreciable flame acceleration. While it can be also defined as the moment when uniform fine cells are distributed over the flame surface. When the flame speed versus flame stretch was measured and the results showed that the SNG flames did not accelerate during the quasi-steady propagation.

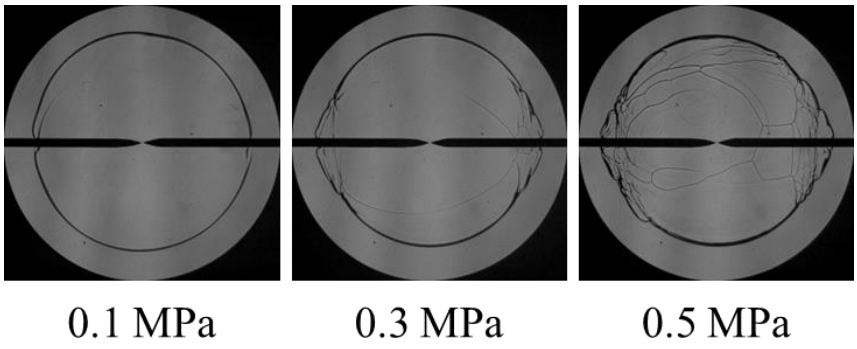

Figure 2: Instantaneous schlieren images of SNG/air premixed flames with ϕ = 1.0 at various initial chamber pressures. The images were taken when the upper flame radius reached 35 mm from the chamber center in the upward direction.

The range of flame radius monitored ($10 \leq R_f \leq 29$ mm) was optimized for the present closed vessel in our previous study [4]. Stretched burning velocity, S_b is defined as dR_f/dt, which R_f is flame radius, and stretch rate, K is expressed as $K = (2/R_f)\, Sb$. There are some methods to determine unstretched laminar burning velocity related to unburned mixture. In the previous study [4], NM II showed the best agreement with the experimental result of laminar burning velocity for methane/air mixture. Thus, unstretched laminar burning velocity, S_b^0 was obtained by NM II which is defined below equation (NM II):

$$\ln(S_b) = \ln\left(S_b^0\right) - S_b^0 L_b \cdot 2/(R_f S_b)$$

From NM II was proposed by Kelly and Law[13], where L_b is Markstein length.

The unstretched laminar burning velocity of unburned gas, S_u^0 can be obtained from the mass conservation. To select the optimized detail kinetic mechanisms, four mechanisms are compared with the measured laminar burning velocities at normal temperature and pressure in Fig. 3. Figure 3(a) shows the experimental laminar burning velocities and the numerical results of four mechanisms with equivalent ratio(ϕ) = 0.7 to 1.4 in SNG/air flame. The symbol denotes the present experimental data, and the lines denote numerical results.

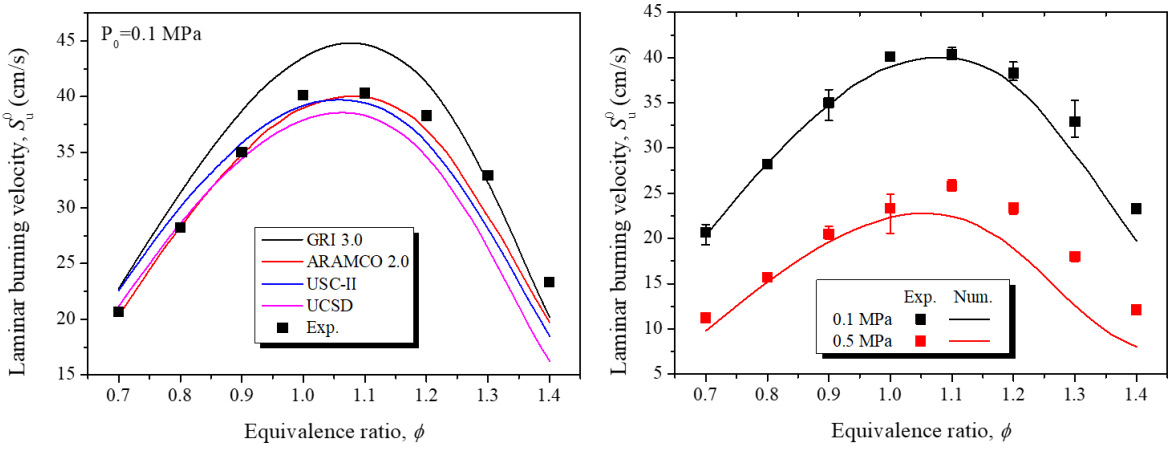

Figure 3: Unstretched laminar burning velocities with respect to unburned mixture against equivalence ratio for SNG/air flames (a) Comparison with four detail kinetic mechanisms, (b) the experimental and numerical(ARAMCO 2.0) laminar burning velocity at 0.1 and 0.5 MPa. The symbols (solid lines) denote experimental (numerical) results.

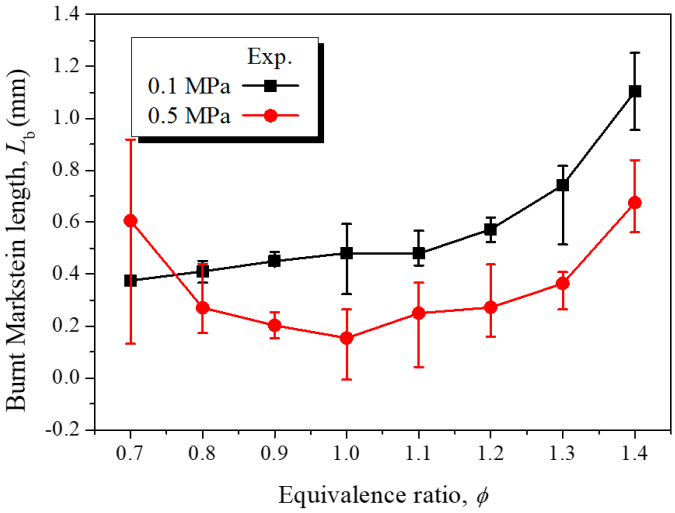

Figure 4: Burnt Markstein lengths for SNG/air flames at 0.1 and 0.5 MPa.

Compared the experimental data, ARAMCO 2.0, USC- II, and UCSD are in a good agreement at lean conditions, while GRI 3.0 is over-predicted, especially ϕ =1.0. At ϕ = 1.4, all mechanism is under-predicted. The deviation is defined as $|S^{o}_{u,exp} - S^{o}_{u,num}|/S^{o}_{u,exp}$, where $S^{o}_{u,exp}$ and $S^{o}_{u,num}$ are the measured and numerical unstretched laminar burning velocities, respectively. The deviation is calculated with each equivalence ratio (from 0.7 to 1.4) and the averaged deviations are compared. The result shows that the best performances are obtained with ARAMCO 2.0. Therefore, in this study, the optimized mechanism for SNG was selected as ARAMCO 2.0, and it is shown in Fig. 3(b) as well. Fig. 3(b) is unstretched laminar burning velocities with respect to unburned mixture in SNG/air premixed flames at initial pressure 0.1 MPa(black) and 0.5 MPa(red). The average values of measured unstretched laminar burning velocities are taken from six experiments. The unstretched laminar burning velocity decreases as the initial pressure rises. At lean flame conditions, numerical results seem quite reasonable in comparison with experimental results. However, as the initial pressure increases, the velocities are deviated appreciably under rich flame conditions, especially at ø = 1.4. For various numerical studies in SNG flames, it can be very useful to evaluate the ARAMCO 2.0.

The burnt Markstein lengths(L_b) from NM II are represented for SNG flames at 0.1 and 0.5 MPa in Fig. 4. The burnt Markstein length has a positive value for all conditions. This means that the instability of the flame surface is suppressed[14]. As the initial pressures of SNG increases, Markstein length decreases, except the case of ϕ = 0.7 at 0.5 MPa. Markstein length at the elevated pressure shows the C -curve in SNG/air flame. This result would be compared with the theoretical Markstein length suggested by Matalon [15].

4 Conclusion

Laminar burning velocity of SNG/air mixtures were determined using outwardly propagation spherical premixed flames in cylindrical constant volume chamber. The experiment was conducted at equivalence ratio 0.7 ~ 1.4 and initial pressure up to 0.5 MPa. SNG fuel was evaluated experimentally and numerically with four chemical kinetics. Unstretched laminar burning velocity of SNG were compared with Aramco 2.0 mechanism. As a result, the tendency for experimental and numerical values were consistent in the lean flame conditions. On the other hand, in the rich flame conditions, the error rate was increased significantly as initial pressure increased. Markstein length of SNG had a positive value under all conditions and at 0.5 MPa, Markstein length showed the C-curves, whereas the 0.1 MPa is linear.

5 Acknowledgement

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