Experimental study of turbulent syngas/methane/air flames at a sub-atmospheric condition

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Abstract. The aim of this work was determined turbulent burning velocities of air-syngas-methane flames at sub-atmospheric conditions using the angle method and Schlieren imaging. We analyzed a high hydrogen content syngas that can be obtained with a Conoco-Phillips coal gasification process. Equivalence ratios evaluated here correspond to lean combustion conditions: 0.8–1.0. Experiments were carried out at room temperature of 297 K and 849 mbar. The chemical-turbulence interaction was evaluated considering geometric parameters, laminar flame properties, and turbulence length scales. It was found that the turbulent burning velocity and the ratio between turbulent and laminar burning velocities increases with the turbulence intensity. Additionally, the addition of syngas to methane increases the laminar and turbulent burning velocity.

1. Introduction

Most modern industrial combustion applications work under turbulent conditions [1]. Thus, the evaluation of fundamental parameters and understanding of related processes to model turbulent flames are critical in order to develop more efficient and cleaner combustion technologies [2]. In this sense, the turbulent burning velocity ($S_T$), is one of the major combustion properties used to describe and analyze premixed flames under turbulent regimes [3]. Currently, there is a lot of research in the estimation of this parameter by mean of various strategies, both, experimentally and numerically [4]. However, the vast majority of these works have been performed using conventional fuels. Just in recent years, alternative fuels such as synthetic gases have started to be considered [5].

Synthetic gas (or syngas) is comprised of a mixture of hydrogen, carbon monoxide, hydrocarbons, and some inert species [2]. The importance of this alternative fuel has been described in numerous studies [2,6], where have been demonstrated that the usage of syngas can help to the diversification of energy sources. Additionally, clean-up processes after the gasification process, as well as the presence of hydrogen in the gas mixture help to reduce pollutant emissions. It is well known that the thermodynamic behaviour of hydrogen exhibits some specific features of interest: high reactivity, high diffusivity, and high concentration of important radicals such as O, H and OH in its flames. However,
hydrogen may also lead to flame instabilities and hydrodynamic instabilities. Therefore, it is worth to take turbulence-chemistry interaction of syngas flames into consideration. [2].

On the other hand, the impact of pressure and temperature on turbulent burning velocities have been extensively studied in order to improve flame stability. Although $S_T$ of different air-fuel mixtures have been obtained as a function of pressure on the basis of experimental data in a wide range of pressures [7], the availability of data of $S_T$ at sub-atmospheric pressures is null. Information of $S_T$ at sub-atmospheric conditions is of special interest to many countries in Latin America because many principal cities are located above sea level.

In this work, we determined turbulent burning velocities of air-syngas-methane flames at sub-atmospheric conditions using the angle method and Schlieren imaging. Equivalence ratios evaluated here correspond to lean combustion conditions: 0.8-1.0. The results are analysed with respect to the laminar burning velocity ($S_L$), which was determined numerically.

2. Methodology

2.1. Experimental setup

Figure 1 shows a schematic illustration of the nozzle-type burner that was used in this work. Air-methane-syngas mixtures are fed into the burner through a plenum, where the mixture is then forced to interact with a perforated plate to induced turbulence. Three perforated plates were designed and implemented to obtain different flow conditions. Here, we considered blockage areas of 77%, 83%, and 88%, which were obtained with orifices of diameter 2.8 mm, 2.4 mm, and 2 mm, respectively. The turbulent flow is discharged through a nozzle of diameter 10 mm. Moreover, a non-premixed pilot flame was implemented to stabilize the turbulent flame. Hydrogen is discharged through a slit of 0.5 mm located around the nozzle. To keep the mixture at constant temperature, cooling water is supplied to the burner. This water flows through cavities within the body of the burner.

![Figure 1. Experimental burner.](image)

Turbulence parameters were determined at the burner outlet assuming Taylor hypothesis and isotropic turbulence. Constant-temperature hot-wire anemometer, mini CTA 54T42 Dantec Dynamics was placed at the centre of the nozzle to register 2400000 data at a frequency of 40 kHz. Mean velocities and their root mean square ($u'$), were computed from these experimental data.

Syngas/CH$_4$ mixtures and equivalence ratios between 0.8 and 1.0 were obtained using a mixing chamber and rotameters that were specifically calibrated for each component gas, similar to those used
The composition of the fuel mixture is shown in the Table 1. It is observed that the addition of syngas to the methane was 30% in volume. The air was provided by an air compressor and dried using water traps. It has been observed in previous studies that with this experimental setup the errors in the final composition is lower than 2% [6].

Table 1. Volumetric compositions of syngas, methane, and syngas-CH₄ mixture.

|       | CH₄ (%) | Syngas (%) | CH₄+Syngas (%) |
|-------|---------|------------|----------------|
| H₂    | -       | 40         | 12             |
| CO    | -       | 40         | 12             |
| CO₂   | -       | 20         | 6              |
| CH₄   | 100     | -          | 70             |

Experiments were performed at a room temperature of 297 K and 849 mbar, that correspond to the atmospheric conditions of Medellin, Colombia. Turbulent burning velocities of air-syngas-methane flames were determined using the angle method and Schlieren imaging [8]. A CCD camera (Basler scA1400-30 gm, 1392 x 1040 pixels, 30 fps) was used to register 60 images of each operating condition, which were processed as described in the next section.

2.2. Image processing

To determine the mean flame cone, the images obtained were processed following the steps described in Figure 2. Basically, the goal of the image processing is to define the contour of the flame in each Schlieren image registered by the CCD camera.

![Image processing](a) Schlieren image, (b) Instantaneous flame front, (c) Overlap of 60 flame fronts.

In this work, we define a progress variable \(c(x,y)\) to determine the mean flame cone, similar to the strategy described by Kobayashi et al. [3] and Wang et al. [9]. The progress variable is 0 in the unburned side of the flame. On the other hand, it takes a value of 1 when the reactive mixture is totally burned. The change from 0 to 1 can be considered to occur immediately and where it takes place can be marked as the flame front. Here, we obtained the mean progress variable \(<c>\) for each set of 60 images, as illustrated in Figure 3(a). Following the work done by [3] and [9], the mean flame cone was identified using \(<c> = 0.1\) with a tolerance of 0.01 as described in Figure 3(b).

\[ S_T = U \sin \left( \frac{\alpha}{2} \right) \]  

Where \(U\) is the mean velocity of the flow, and \(\alpha\) is the flame angle.
2.3. Laminar burning velocity

Laminar burning velocities, $S_L$, (which are used to analyse the results) were computed using the detailed kinetic mechanism USC II [12] and the packages PREMIX and EQUIL (ANSYS Chemkin [13]), as described in [10,11]. Previous studies have shown that the detailed kinetic mechanism USC II predicts very well $S_L$ for the methane and different syngas mixtures [14].

3. Results and discussions

Figure 4 shows the numerical laminar burning velocity for CH$_4$/air and syngas/CH$_4$/air mixtures. It is observed that the addition of syngas to methane increases $S_L$. This behaviour can be attributed to the hydrogen in the syngas. Its high reactivity accelerates the reaction process and therefore $S_L$ increases. Moreover, Figure 4 include experimental data of $S_L$ for methane and syngas, the data were obtained by Cardona et al. [14] and Burbano et al. [11] respectively. It is possible to see that the prediction shows a good agreement between numerical and experimental results for both, CH$_4$/air mixture and syngas/air mixtures.

Turbulent premixed flames can be categorized into five regimes, as illustrated in Figure 5. These regimes are defined by laminar flame thickness, Kolmogorov microscale, and integral scale. The
laminar flame thickness was calculated by $\delta_l = D_{th}/S_L$, where, $D_{th}$ is the thermal diffusivity of the unburned mixtures, and $S_L$ is the laminar burning velocity of the mixtures. Figure 5 shows the turbulent premixed flames studied in this work. This figure correspond to the Borghi’s diagram modified by Peters [15]. It is observed that all flames examined here are located in the flamelet regime.

Figure 6 presents normalized values of $S_r$ and $u'$ against $S_L$. This figure also includes the results obtained by Kobayashi et al [16] and Zhang et al [17]. The increase of turbulent burning velocity in the syngas/CH$_4$/air mixture respect to the CH$_4$/air mixture is again attributed to the H$_2$.

Figure 7 shows the turbulent burning velocities obtained for the CH$_4$/air and syngas/CH$_4$/air mixtures with the perforated plate with a blockage area of 88%. It is observed that $S_r$ decreases as the equivalence ratio decrease. Moreover, the addition of syngas to natural gas increases turbulent burning velocity up to 10.3%.

![Figure 5. Borghi’s diagram.](image1)

![Figure 6. Turbulent burning velocity.](image2)

![Figure 7. Turbulent burning velocity for CH$_4$/air and syngas/CH$_4$/air mixtures with the perforated plate with a blockage area of 88%.](image3)
4. Conclusions
In this work, turbulent burning velocities of methane-air and syngas-methane-air mixtures were determined at a sub-atmospheric condition. Additionally, the chemical-turbulence interaction was evaluated considering geometric parameters, laminar flame properties, and turbulence length scales.

In general, adding syngas to CH₄ leads to an increase of $S_r/S_l$ as $u'/S_l$ increases. This behaviour is also observed for CH₄, however the rate of the increase of $S_r/S_l$ for the syngas/CH₄/air mixture is higher than CH₄/air mixtures. This result can be attributed to the hydrogen diffusivity. Adding syngas to CH₄ reduce blow off tendency, which can be explained by the increase in $S_r$. The addition of syngas increases the turbulent burning velocity up to 10.3%.

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