Burning Velocity of Turbulent Methane/Air Premixed Flames in Subatmospheric Environments

Arley Cardona Vargas, Alex M. García, Carlos E. Arrieta, Jorge Sierra del Rio, and Andrés Amell*

ABSTRACT: The aim of our work was to study turbulent premixed flames in subatmospheric conditions. For this purpose, turbulent premixed flames of lean methane/air mixtures were stabilized in a nozzle-type Bunsen burner and analyzed using Schlieren visualization and image processing to calculate turbulent burning velocities by the mean-angle method. Moreover, hot-wire anemometer measurements were performed to characterize the turbulent aspects of the flow. The environmental conditions were 0.85 atm, 0.98 atm, and 295 ± 2 K. The turbulence–flame interaction was analyzed based on the geometric parameters combined with laminar flame properties (which were experimentally and numerically determined), integral length scale, and Kolmogorov length scale. Our results show that the effects of subatmospheric pressure on turbulent burning velocity are significant. The ratio between turbulent and laminar burning velocities increases with turbulence intensity, but this effect tends to decrease as the atmospheric pressure is reduced. We propose a general empirical correlation as a function between $S_T/S_L$ and $u'/S_L$ based on the experimental results obtained in this study and the equivalence ratio and pressure we established.

1. INTRODUCTION

In the last years, natural gas has become a very interesting alternative fuel for the manufacturing industry and in electric power production. This has been motivated largely by the fact that natural gas produces less pollutant emissions per unit energy than other fossil fuels. Several studies on the matter agree that lean-burn natural gas applications are particularly interesting because they have the potential to radically reduce NOx emissions and improve thermal efficiencies. However, lean combustion applications demand operation at or close to lean blowout, which may eventually lead to safety issues. Therefore, fundamental studies of flame stability have important practical applications because they provide relevant information for the design and operation of modern combustors. Generally, researchers are interested in parameters that give information about chemical kinetics and turbulent–chemistry interaction such as turbulent burning velocity ($S_T$).

The effect of operating conditions such as fuel-to-air ratios, turbulence intensity, temperature, and pressure on $S_T$ has drawn special attention in combustion studies, especially to ensure adequate flame stability limits. However, most of these studies have been conducted at a standard sea-level (atmospheric) pressure and under high-pressure conditions. For example, Kobayashi et al.,1–7 Shy et al.,8 and Smallwood9 studied turbulent premixed flames at high pressures keeping constant the length of the integral scale and the average velocities of the flows. Similarly, Jiang et al.10–12 studied mixtures of hydrogen and carbon monoxide in turbulent conditions at atmospheric pressure and temperature, and the experiments were carried out in a spherical turbulent combustion bomb. In general, they found that the equivalence ratio or hydrogen fraction increased, the dimensionless turbulent flame propagation speed decreased, and the normalized turbulent burning velocity increased as the turbulence intensity increased. The distribution of the flame local propagation speed presented a normal distribution under a turbulent environment. With the increase of the turbulence, the components of higher flame local propagation speed increased. Although several important conclusions have been drawn from these studies with regard to the relationship between $S_T$ with other combustion properties, such as laminar burning velocity ($S_L$), to the best of our knowledge, the number of studies into $S_T$ at subatmospheric pressures is still limited. Goldenberg and Pelevin13 investigated turbulent burning velocities of methane and gasoline flames at pressures ranging from 1 to 0.13 atm. Using gasoline in a turbulent regime, they varied the Reynolds number from 4000 to 20,000 and the relative turbulence intensity from 4 to 5%. The results showed that as pressure decreases, $S_T$ increases. For a Reynolds number of 4000 with a
concentration of gasoline in air of 2.4%, it was found that for a pressure of 1 atm, a turbulent burning velocity of 55.5 cm/s was observed and for a pressure of 0.13 atm, a turbulent burning velocity of 95.3 cm/s was observed, which corresponds to an increase in percentage of approximately 71%. Khramtssov\textsuperscript{14} studied the influence of pressure on the turbulent parameters and the turbulent burning velocities of propane. The experiments were carried out at pressures of 0.6, 0.3, and 0.1 atm. The study was conducted for propane combustion. It was found that the relationship between $S_T$ and pressure follows the equation $S_T \sim P^{0.12}$ when turbulence intensity change, while the equation $S_T \sim P^{0.5}$ applies when the turbulence intensity is constant.

Schorn et al.\textsuperscript{15} studied jet turbulent premixed flames using a piloted Bunsen burner. The fuel types they examined were jet-A (a conventional jet fuel) and two surrogate fuels that have thermophysical properties like those of jet-A: ATJ Gevo and C10/TMB. The turbulent burning velocity varied from 1.5 to 3 m/s at two pressures, 71 kPa (0.701 atm) and 101 kPa (1 atm), and had equivalence ratios of 0.8 – 1.0. In general, they found that the turbulent burning velocity increase as pressure is reduced at lean operating conditions. At an equivalence ratio of 0.8 and subatmospheric pressure, the laminar burning velocity increased with all the fuels (compared to an atmospheric pressure). At subatmospheric pressure, the relationship between the normalized burning velocity and normalized turbulent fluctuations was inverted because of the atmospheric condition. Cardona et al.\textsuperscript{16} studied syngas/methane/air flames at subatmospheric conditions. The equivalence ratios they evaluated correspond to lean combustion conditions: 0.8–1.0. Their experiments were carried out at a room temperature of 297 K and 849 mbar (0.85 atm). The chemical–turbulence interaction was evaluated considering geometric parameters, laminar flame properties, and turbulence length scales. They found that the turbulent burning velocity and the ratio between turbulent and laminar burning velocities increase with the turbulence intensity. Additionally, the addition of syngas to methane increases the laminar and turbulent burning velocities. The addition of syngas increases the turbulent burning velocity up to 10.3%. As previously discussed, studies at high pressure conditions have also shown that $S_L$ plays an important role to study $S_T$.

$S_T$ is defined as the speed at which the flame front propagates toward the gas mixture without burning at adiabatic conditions, laminar flow, and unstressed flame.\textsuperscript{17} Contrary to what was observed for $S_{TR}$, several studies into $S_L$ have been conducted at subatmospheric conditions.\textsuperscript{18–22} It has been found that the global order of the reaction ($n$) is the parameter responsible for the dependence of $S_L$ on pressure. Furthermore, an analytical expression for the speed of laminar deflagration as a function of pressure is $S_L \propto P^{(n-2)/2}$.\textsuperscript{23} This means that pressure decreases the rate of laminar combustion when the overall order of the reaction is $n < 2$, and the opposite is the case when $n > 2$. The value of $n$ depends on the fuel-oxidizing mixture. Egolfopoulos and Law\textsuperscript{16} performed $S_L$ measurements of CH$_4$/air mixtures at different pressures. In all the mixtures, they studied that $n$ was less than 2; hence, $S_L$ always decreased as pressure increased.

The effect of pressure was greater in the subatmospheric range, where they obtained a decrease in the $S_L$ value of 27% when they changed from 0.5 to 1 atm in the stoichiometric case. These results are in line with those presented by Kobayashi et al.,\textsuperscript{4} Andrews and Bradley,\textsuperscript{24} and Mauss and Peters.\textsuperscript{25} The latter proposed a relationship between the laminar burning velocity ($S_L$) and pressure ($P$) measured using the burner method at three equivalence ratios ($\phi = 0.9, \phi = 1.0$, and $\phi = 1.1$). Their study shows that $S_L$ decreases as pressure increases, and the exponent that best fits all the pressure data is −0.5. They proposed an approximate ratio for these data as a function of pressure, $S_L = 0.34(P/P_0)^{-0.5}$, where $P_0$ is the atmospheric reference pressure in MPa.

Information about $S_T$ of natural gas at subatmospheric pressure is particularly relevant for Latin American countries, where many cities—with intensive manufacturing and industrial activity—are located at high altitudes above the sea level. Additionally, because practical burners generally work with forced air (supplied by a blower) and under a lean combustion regime, it is important to have information about $S_T$ at these fuel-to-air ratios. For these reasons, in this study, turbulent burning velocities of natural gas (100% CH$_4$) were experimentally determined at two subatmospheric conditions and two equivalence ratios. Flames were generated in a nozzle-type Bunsen burner and then analyzed using Schlieren photography. The experimental setup and methodology to obtain $S_T$—which are discussed below—have been used before by Kobayashi et al.,\textsuperscript{1} Rangwala et al.,\textsuperscript{26,27} Wang et al.,\textsuperscript{28,29} Cardona et al.,\textsuperscript{16} and Grover et al.\textsuperscript{30} for methane and different hydrocarbon mixtures.

It has been reported that this methodology is one of the most appropriate one to obtain $S_T$ because flames are stationary, and it is possible to perform long-time measurements. Several groups of researchers have also implemented similar methodologies for other operating conditions and fuels, such as hydrogen—syngas mixtures\textsuperscript{16,28,29,31} and coal dust on premixed turbulent methane/air flames.\textsuperscript{26,27,32}

## 2. METHODOLOGY

### 2.1. Chemical Composition of the Gases

High-purity certified gases and rotameters specifically calibrated were used to prepare the methane/air mixtures. Table 1 details the purity of the pure methane (as specified by the supplier) used to emulate the gas compositions and pure hydrogen for the nonpremixed pilot flames.

### 2.2. Perforated Plate Selection

Turbulence intensity is generated using different perforated plate configurations and hole diameters. Perforated plates were selected based on previous studies.\textsuperscript{5,6,33} In this work, we implemented three perforated plates. Therefore, three levels of turbulence intensity were evaluated. Table 2 and Figure 1 show all the geometrical parameters of the perforated plates, where $\sigma$ is the relation between the block area and total flow area. The external diameter is 20 mm which corresponds to the flow free area.

### 2.3. Experimental Setup

Premixed turbulent flames were generated by a nozzle-type Bunsen burner with a nozzle internal diameter of 10 mm, as shown in Figure 2. Turbulence was

### Table 1. Stated Composition of the Gases

| gas          | purity (%) | CH$_4$ | CO + CO$_2$ | H$_2$O | C$_2$H$_6$ | H$_2$ | THC< 1 ppm |
|--------------|------------|--------|-------------|--------|-----------|------|------------|
| CH$_4$       | 99.99      | N$_2$ < 30 ppm | O$_2$ < 5 ppm | H$_2$O < 10 ppm | C$_2$H$_6$ < 300 ppm | H$_2$O < 10 ppm |
| H$_2$        | 99999      |        |             |        |           |      |            |

“THC (total hydrocarbon content).
generated by a perforated plate installed 42 mm upstream the nozzle outlet. A circular pilot flame slit with a thickness of 0.5 mm was designed around the nozzle outlet to support the flame. As reported in other studies by Kobayashi et al.\(^\text{28,29}\) and Wang et al.\(^\text{28,29}\), this burner design improves flame stability, which is essential for long-time measurements. Hydrogen is discharged through the circular slit, generating a nonpremixed flame that is used to ignite the fuel–air mixture and anchor the main premixed flame to the burner nozzle. Cooling water is supplied through cavities in the steel burner body to prevent the preheating of the fuel through cavities in the steel burner body to prevent the preheating of the fuel–air mixture and excessive temperature levels in the nozzle. The mean velocity at the nozzle outlet was controlled between approximately 2 and 5 m/s to prevent flame flashback and blowoff.

The experiments were carried out in a range from lean to stoichiometry conditions, and the equivalence ratio was varied from 0.8 to 1.0 and was conducted at local atmospheric conditions at 1550 m.a.s.l (0.85 atm, 295 ± 2 K) and 210 m.a.s.l (0.98 atm, 295 ± 2 K). In this experimental setup, the air was supplied by an air compressor and dried using two inline water traps. Each fuel-to-air ratio and exit flow velocity was achieved using rotameters that were specifically calibrated for each gas component, similar to those used in refs \(^\text{22,24}\) and \(^\text{34}\). The errors in the final fuel–air mixture composition were estimated at under 2%.

The turbulence parameters were measured using a constant-temperature hot-wire anemometer (MiniCTA 54T42 Dantec Dynamics) at the center of the nozzle outlet with a single 1D-SSP11 probe. Turbulent flow parameters (such as turbulence intensity \(u'\), integral length scale \(l_o\), integral Reynolds \(R_l\) and integral Reynolds \(R_l\)) were calculated assuming Taylor’s hypothesis and isotropic turbulence. At each operating condition, 2,400,000 data were registered at a frequency of 40 kHz. Mean flow velocity and its root means square, \(u'\), were calculated from the recorded data as proposed by Kobayashi et al.\(^\text{2,3,4}\) and Rangwala et al.\(^\text{16,27}\).

Table 2 shows the flow parameters measured at pressure conditions of 0.98 and 0.85 atm and an equivalence ratio \(\phi = 1.0\). The integral length scale \(l_o\) and the Kolmogorov length scale \(l_h\) were measured at the center of the nozzle outlet at some flow velocities. As can be seen, the turbulence scales decrease as pressure increases, but the Kolmogorov length scale tends to become almost constant.

The turbulence measurements were performed in cold flow without flame, similar to Kobayashi et al.\(^\text{1,2}\) or Wang et al.\(^\text{28,29}\). Air–methane mixture flow rates between 3 and 6 m/s were used to create turbulent intensities up to 0.303 m/s. The turbulent flow can be described using eq 1, where \(u'\) is the fluctuating component of the flow velocity; \(u\) the flow velocity; and \(\bar{u}\), the average flow velocity. Turbulence resistance is generally characterized by the relative turbulence intensity \(u'\), which is the ratio between the mean square root of the fluctuations \(u'(t)\) and the average value \(\bar{u}\); hence, the expression to determine the turbulence intensity is given by eq 2.

\[
\begin{align*}
\bar{u} & = u(t) - u \\
u' & = \sqrt{\overline{u(t)^2}}/\bar{u}
\end{align*}
\]

The integral length scale \(l_o\) of turbulence is calculated using \(l_o = \bar{u}\tau\) (eq 3), where \(\tau\) is the integral time scale calculated by eq 4, where \(\bar{u}\) is the average flow velocity, and \(\rho(\tau)\) is the autocorrelation of the velocity fluctuation. For the discrete samples, the integral time scale is calculated using the methodology described by Tyagi et al.\(^\text{35}\), where N is the number

![Figure 1. Geometries of the perforated plates (metric measures).](https://dx.doi.org/10.1021/acsomega.0c02670)
of samples, as seen in eq 5. Figure 3 shows the autocorrelation of the velocity fluctuation at $u' = 0.275 \text{ m/s}$, $\phi = 1.0$, and 0.85 atm.

$$l_0 = \bar{u} \int_0^\infty \rho(\tau) \mathrm{d}\tau$$  \hspace{1cm} (3)

$$\tau = \int_0^\infty \rho(\tau) \mathrm{d}\tau$$  \hspace{1cm} (4)

$$\tau = \left( \sum_{i=1}^{N-1} \rho(i\Delta t) \right) \Delta t$$  \hspace{1cm} (5)

Schlieren measurements were performed to identify the instantaneous flame front structure of the turbulent premixed flames. To ensure experimental repeatability, every operating condition included in the experiments of laminar and turbulent burning velocities was evaluated three times. It was found that the repeatability was excellent, as previously reported by Kobayashi et al.,4,5,7 Rangwala et al.,26,27 Smallwood,9 and Wang et al.28,29 A scheme of the experimental setup is presented in Figure 4. For the Schlieren technique, the light source was a high-intensity xenon lamp. A biconvex lens (diameter: 50.8 mm, focal length: 38.1 mm) and a pinhole were used to focus the light toward the probe zone using a plano-convex lens (diameter: 50.8 mm, focus length: 250 mm). Another plano-convex lens (diameter: 50.8 mm, focus length: 250 mm) was used to focus the beam on a spot with a knife edge. The part of the beam disturbed by the flame was blocked by the knife edge, while the rest was captured by a high-resolution CCD camera (Basler scA1400-30 gm, 1392 $\times$ 1040 pixels, 30 pps). The images were captured using a camera lens (Canon, diameter: 49 mm, focus length: 50 mm, f/1.8) and subsequently postprocessed on a computer.

The turbulent burning velocities were determined using the mean angle method similar to the one adopted by Rangwala et al.26,27 and Grover et al.,30 who averaged the measured flame height in several images to determine the burning velocity of a turbulent flame. Measurements of the turbulent burning velocity using a Bunsen-type burner and a flame-angle method have been widely implemented by many authors. Our results are in agreement with those reported in many studies based on a large number of experimental data.9,36

In the angle method, the angle of the flame cone profile is determined from images of the flame front, as illustrated in Figure 5. In this way, the turbulent burning velocity ($S_T$) can be defined by eq 6, where $\alpha$ is the mean inner flame front cone angle, and $U$ is the mean velocity of the mixture at the burner outlet. To obtain stable flames and avoid flashback and blowout effects, this study implemented the methodology described by Kobayashi et al.4-7

$$S_T = U \sin(\alpha/2)$$  \hspace{1cm} (6)

2.4. Image Processing. The mean flame cone was determined by processing the Schlieren images. The steps for image processing are shown in Figure 6. First, the instantaneous flame front was obtained from each Schlieren image. For each measurement, a total of 60 images were registered; thus, 60 different instantaneous flame fronts were obtained at each operating condition. The progress variable ($c$) was used to determine the mean flame cone, following the methodology described by Kobayashi et al.6 and Wang et al.28 The progress variable takes a value of 0 in the unburned side of the flame and a value of 1 when the reactive mixture is totally burned. The change from 0 to 1 is considered to occur immediately in the flame front, as described by Kobayashi et al.6 Figure 6d shows a contour of the mean progress variable ($\langle c \rangle$), which is calculated by averaging the progress variable of the 60 images. In Figure 6d, a value of $\langle c \rangle$ between 0 and 1 does not represent an intermediate reaction state between unburnt and burnt; instead,
it implies that at that location, the fluctuating turbulent flame spends sometime in the unburnt state and the remainder in the burnt state. Following the work of Kobayashi et al.\textsuperscript{5, 6} and Wang et al.,\textsuperscript{28} \( S_f \) was defined as a function of the mean flame cone using \( \langle c \rangle = 0.1 \) with a tolerance of 0.01, as described in Figure 6e.

The number of images required to calculate the turbulent burning velocity was determined by conducting a parametric study, as shown in Figure 7. \( S_f \) was calculated using a different methodology described in previous works.\textsuperscript{22, 34, 37} The detailed mechanism selected for the calculations was GRI-Mech 3.0.\textsuperscript{40}

Figure 8 shows the experimental and numerical results of the laminar burning velocity at a room temperature of 298 K and atmospheric pressures of 0.85 and 0.98 atm.

A good agreement was observed between the experimental and numerical results: the differences did not exceed 8%. However, it was not possible to obtain experimental results of \( S_f \) at 0.98 atm and \( \phi = 0.8 \) because of the occurrence of flame blowoff; thus, in the analysis in this paper, regarding this operating condition, we used results previously reported by Vagelopoulos and Egolfopoulos.\textsuperscript{41}

Figure 8 also shows that the experimental and numerical results of \( S_f \) at 0.98 atm are lower than those obtained at 0.85 atm. At an equivalence ratio of 1.0 and 0.85 atm, the laminar burning velocity was 40.04 cm/s, while at 0.98 atm, the said velocity was 36.53 cm/s. This difference is in agreement with the values expected for a 9% variation in atmospheric pressure.\textsuperscript{41}

3. RESULTS AND DISCUSSION

3.1. Laminar Burning Velocity. Turbulent burning velocity results are normally presented based on the laminar burning velocity (\( S_L \)) at the same conditions. In this study, \( S_L \) was also determined at the same conditions, experimentally and numerically. The burner method was implemented to determine \( S_L \) experimentally. This method for laminar flow regimes is described in detail in refs 22, 34, 37. Additionally, the numerical laminar burning velocities were calculated by means of Chemkin-Pro\textsuperscript{38} software; in particular, the packages Premix\textsuperscript{39} and Equil were used, following the methodology described in previous works.\textsuperscript{22, 34, 37}

The number of images required to calculate the turbulent flame velocity results are normally presented based on the laminar burning velocity.

Figure 7 shows the laminar burning velocity as a function of the mean number of images (at \( \phi = 1.0 \) and 0.85 atm).

Figure 8. Laminar burning velocity.
3.3. Turbulent Burning Velocity and Validation Study. Figure 10 presents the results of the turbulent burning velocity at the operating conditions that were considered in this study. Both, $S_T$ and $u'$ were normalized against $S_L$, as indicated in the said figure. For comparative purposes, results at 0.99 and 1 atm reported previously by Kobayashi et al.,6 Rockwell and Rangwala,26 Wang et al.,29 and Zhang et al.31 are also included.

It can be seen that the results obtained in this study at atmospheric conditions are in the same order of magnitude as the data available in the literature. In general, different results were obtained at the same pressure and equivalence ratio; nevertheless, the interaction with the turbulence intensity modified the results for the turbulence burning velocity. In this study, three different types of plates were used to generate a wide range of turbulence conditions, with $\sigma = 88\%$, $\sigma = 83\%$, and $\sigma = 77\%$, and the turbulence intensity measured at the center of the nozzle outlet reached 0.303 m/s.

In addition, Figure 11 presents the results of $S_T$ as a function of $u'$. Data reported by Kobayashi et al.6 and Rockwell and Rangwala26 were also included. In the said figure, it can be seen that contrary to the values of $S_T$ obtained in this study, the results at 0.85 atm are lower than those obtained at 0.98 atm.

At $\phi = 1$ and a turbulence intensity of approximately 0.24 m/s, the turbulent burning velocity was reduced by 5% when the atmospheric condition changed from 0.85 to 0.98 atm. At $\phi = 0.8$, the reduction in $S_T$ with the same change in atmospheric pressure was 15% at a turbulence intensity of about 0.19 m/s, and it was 4% at a turbulence intensity between 0.32 and 0.33 m/s.

At an atmospheric pressure of 0.98 atm and a turbulence intensity around 0.14 m/s, there was a reduction in the turbulent burning velocity of 4%, moving from $\phi = 1$ to $\phi = 0.8$. In turn, at a turbulence intensity around 0.17 m/s, the reduction in $S_T$, with the same change in the equivalent ratio, was 10%. At an atmospheric pressure of 0.58 atm and a turbulence intensity of around 0.42 m/s, the reduction in $S_T$ was about 12% as the equivalent ratio decreased from 1 to 0.8.

Table 4 shows the effects of pressure on the thermophysical properties of the CH$_4$/air mixture. The decrease in kinematic viscosity, $v$, with increasing pressure is a major factor that determines the characteristics of the turbulence. Because the change in viscosity, $\mu$, with pressure is very small, the kinematic viscosity is almost inversely proportional to the density, $\rho$, and, thus, to pressure. As shown in Table 3, the variation of the integral length scale with pressure plays an additional role in the
Table 4. Effects of Pressure on the Thermophysical Properties of the Mixture and Adiabatic Flame Temperature (CH₄/Air, 295 K)

| pressure (atm) | equivalence ratio, $\phi$ | density, $\rho$ (kg/m³) | viscosity, $\mu$ (Pa·s) | kinematic viscosity, $v$ (m²/s) | thermal diffusivity ($\alpha$) (m²/s) | Lewis number of fuels | Prandtl number, $Pr$ | adiabatic flame temperature (K) |
|---------------|--------------------------|-------------------------|------------------------|-------------------------------|--------------------------------------|-----------------------|----------------|-----------------------------|
| 0.98          | 1.0                      | 1.108                   | 1.788 × 10⁻⁵           | 1.613 × 10⁻⁵                  | 2.101 × 10⁻⁵                       | 1.007                 | 0.768          | 2223                        |
|               | 0.8                      | 1.117                   | 1.799 × 10⁻⁵           | 1.610 × 10⁻⁵                  | 2.116 × 10⁻⁵                       | 0.963                 | 0.761          | 1933                        |
| 0.85          | 1.0                      | 0.956                   | 1.778 × 10⁻⁵           | 1.860 × 10⁻⁵                  | 2.421 × 10⁻⁵                       | 1.007                 | 0.768          | 2219                        |
|               | 0.8                      | 0.964                   | 1.789 × 10⁻⁵           | 1.856 × 10⁻⁵                  | 2.438 × 10⁻⁵                       | 0.963                 | 0.761          | 1992                        |

Figure 12. Correlation of turbulent burning velocities $S_T/S_L$ and $u'/S_L$ of CH₄/air at 0.85 and 0.98 atm (295 K).

Two main conclusions:

1. The theoretical estimates at pressures $P = 0.74$ atm and $P = 0.63$ based on eq 8 are also presented in Figure 12. Although it is necessary to perform experimental measurements at these pressure conditions to validate our model, the results show that reducing the atmospheric pressure decreases the slope of $S_T/S_L$ as a function of $u'/S_L$, which indicates a reduction in the effect of turbulence intensity on turbulent burning velocity.

2. 4. CONCLUSIONS

We performed experimental measurements of the turbulent burning velocity of methane with normal air at 0.85, 0.98 atm, room temperature of 295 ± 2 K, and different equivalence ratios. Based on an analysis of the experimental results we obtained, we can draw three main conclusions:

- Reduction in atmospheric pressure decreases the slope of $S_T/S_L$ as a function of $u'/S_L$, which indicates a reduction in the effect of turbulence intensity on turbulent burning velocity.

- Higher frequencies of velocity fluctuations (smaller vortices) have relatively larger energy densities, meaning that the turbulence structure becomes finer as pressure increases.

- Turbulence intensity is directly proportional to the kinematic viscosity, meaning that the turbulence structure becomes finer as pressure increases.

3. General Correlations of Turbulent Burning Velocity. In previous studies, general correlations of turbulent burning velocities have been proposed following a power-law function of the form:

$$ S_T/S_L \propto (u'/S_L)^n $$

In this study, we propose a correlation that accounts for the pressure effects in subatmospheric environments

$$ S_T S_L = 3.18 \left( \frac{P}{P_0} \right)^{0.96} \left( \frac{u'}{S_L} \right)^{1.48} \left( \frac{\rho}{\rho_0} \right)^{0.53} $$

The theoretical estimates at pressures $P = 0.74$ atm and $P = 0.63$ based on eq 8 are also presented in Figure 12. Although it is necessary to perform experimental measurements at these pressure conditions to validate our model, the results show that reducing the atmospheric pressure decreases the slope of $S_T/S_L$ as a function of $u'/S_L$, which indicates a reduction in the effect of turbulence intensity on turbulent burning velocity.
1. The effects of pressure on the turbulent burning velocity in this study show a tendency: at 0.85 atm, the turbulent burning velocity is lower than that at 0.98 atm, and there is a decrease of up to 16% in turbulent burning velocity at 0.85 atm with respect to 0.98 atm (near sea level). These results were obtained at the same conditions of turbulence intensity, discharge speed in the burner port, and room temperature.

2. A general empirical correlation can be proposed as a function between $S_f/S_L$ and $u'/S_L$ based on the experimental results obtained in this study using the equivalence ratio and pressure established above. Such empirical correlation is of the form $S_f/S_L = C_1(P/P_0)^{C_2} (u'/S_L)^{C_3}$. At 0.98 and 0.85 atm, the correlation constants are $C_1 = 3.18$, $C_2 = 1.48$, and $C_3 = 0.53$.

3. The characteristics of premixed turbulent flames depend largely on the regimes, which are defined by the thickness of the laminar flame, the turbulence intensity, the laminar burning velocity, the integral scale, and the Kolmogorov microscale, as well as by dimensionless numbers such as the Damkohler number and the Karlovitz number. The flames in the present study are in the flamelet regime. In this regime, there are $Da \gg 1$ numbers and a rapid chemistry regime is defined because the chemical reaction rates are much faster than the flow mixing rates.

**REFERENCES**

1. Kobayashi, H.; Kawazoe, H. Flame instability effects on the smallest wrinkling scale and burning velocity of high-pressure turbulent premixed flames. *Proc. Combust. Inst.* 2000, 28, 375–382.

2. Kobayashi, H.; Kawabata, Y.; Maruta, K. Experimental study on general correlation of turbulent burning velocity at high pressure. *Symp. Combust.* 1998, 27, 941–948.

3. Kobayashi, H.; Kawahata, T.; Seyama, K.; Fujimori, T.; Kim, J.-S. Relationship between the smallest scale of flame wrinkles and turbulence characteristics of high-pressure, high-temperature turbulent premixed flames. *Proc. Combust. Inst.* 2002, 29, 1793–1800.

4. Kobayashi, H.; Nakashima, T.; Tamura, T.; Maruta, K.; Niioka, T. Turbulence measurements and observations of turbulent premixed flames at elevated pressures up to 3.0 MPa. *Combust. Flame* 1997, 108, 104–117.

5. Kobayashi, H. Experimental study of high-pressure turbulent premixed flames. *Exp. Therm. Fluid Sci.* 2002, 26, 375–387.

6. Kobayashi, H.; Seyama, K.; Hagiwara, H.; Ogami, Y.; Aldredge, R. Burning velocity correlation of methane/air turbulent premixed flames at high pressure and high temperature. *Proc. Combust. Inst.* 2005, 30, 827–834.

7. Kobayashi, H.; Tamura, T.; Maruta, K.; Niioka, T.; Williams, F. A. Burning velocity of turbulent premixed flames in a high-pressure environment. *Symp. Combust.* 1996, 26, 389–396.

8. Shy, S. S.; Lin, W.; Wei, J. An experimental correlation of turbulent burning velocities for premixed turbulent methane-air combustion. *Proc. R. Soc. London, Ser. A* 2000, 456, 1997–2019.

9. Smallwood, G. Characterization of flame front surfaces in turbulent premixed methane/air combustion. *Combust. Flame* 1995, 101, 461–470.

10. Jiang, Y.-h.; Li, G.-x.; Li, H.-m.; Zhang, G.-p.; Lv, J.-c. Experimental Study on the Self-Similar Propagation of H2/CO/Air Turbulent Premixed Flame. *Energy Fuels* 2019, 33, 12736–12741.

11. Jiang, Y.-h.; Li, G.-x.; Li, H.-m.; Li, L.; Zhang, G.-p. Experimental study on the turbulent premixed combustion characteristics of 70%H2/30%CO/air mixtures. *Int. J. Hydrogen Energy* 2019, 44, 14012–14022.

12. Li, H.-M.; Li, G.-X.; Jiang, Y.-H.; Li, L.; Li, F.-S. Flame stability and propagation characteristics for combustion in air for an equimolar mixture of hydrogen and carbon monoxide in turbulent conditions. *Energy* 2018, 157, 76–86.

13. Goldenberg, S. A.; Pelevin, V. S. Influence of pressure on rate of flame propagation in turbulent flow. *Symp. Combust.* 1958, 7, 590–594.

14. Khramtsov, V. A. Investigation of pressure effect on the parameters of turbulence and on turbulent burning. *Symp. Combust.* 1958, 7, 609–614.

15. Schorn, N.; Bonebrake, J. M.; Pendergrass, B.; Fillol, A. J.; Bluncck, D. L. Turbulent consumption speed of large hydrocarbon fuels at sub-atmospheric conditions. *AIAA SciTech* 2019, Forum, 2019; pp 1–8.

16. Cardona, A.; Garcia, A.; Cano, F.; Arrieta, C. E.; Yepes, H. A.; Amell, A. Experimental study of turbulent syngas/methane/air flames at a sub-atmospheric condition. *J. Phys.: Conf. Ser.* 2019, 1409, 012012.

17. Yu, G.; Law, C. K.; Wu, C. K. Laminar flame speeds of hydrogen+ air mixtures with hydrogen addition. *Combust. Flame* 1986, 63, 339–347.

18. Egolfopoulos, F. N.; Law, C. K. Chain mechanisms in the overall reaction orders in laminar flame propagation. *Combust. Flame* 1990, 80, 7–16.

19. Egolfopoulos, F. N.; Law, C. K. An experimental and computational study of the burning rates of ultra-lean to moderately-rich H2/O2/N2 laminar flames with pressure variations. *Symp. Combust.* 1991, 23, 333–340.

20. Konnov, A. A.; Riemerjeier, R.; de Goey, L. P. H. Adiabatic laminar burning velocities of CH4+H2+air flames at low pressures. *Fuel* 2010, 89, 1392–1396.

21. Kuznetsov, M.; Kobelt, S.; Grune, J.; Jordan, T. Flammability limits and laminar flame speed of hydrogen-air mixtures at sub-atmospheric pressures. *Int. J. Hydrogen Energy* 2012, 37, 17580–17588.
(22) Burbano, H. J.; Pareja, J.; Amell, A. A. Laminar burning velocities and flame stability analysis of syngas mixtures at sub-atmospheric pressures. Int. J. Hydrogen Energy 2011, 36, 3243–3252.
(23) Turns, S. R. An Introduction to Combustion Concepts and Applications; McGraw Hill Higher Education: Singapore, 2000.
(24) Andrews, G. E.; Bradley, D. The burning velocity of methane-air mixtures. Combust. Flame 1972, 19, 275–288.
(25) Mauss, F.; Peters, N. Reduced Kinetic Mechanisms for Applications in Combustion Systems; Peters, N., Rogg, B., Eds.; Springer-Verlag: New York, 1993; p 72. n.d.
(26) Rockwell, S. R.; Rangwala, A. S. Influence of coal dust on premixed turbulent methane-air flames. Combust. Flame 2013, 160, 635–640.
(27) Ranganathan, S.; Petrow, D.; Rockwell, S. R.; Rangwala, A. S. Turbulent burning velocity of methane–air–dust premixed flames. Combust. Flame 2018, 188, 367–375.
(28) Wang, J.; Zhang, M.; Xie, Y.; Huang, Z.; Kudo, T.; Kobayashi, H. Correlation of turbulent burning velocity for syngas / air mixtures at high pressure up to 1.0 MPa. Exp. Therm. Fluid Sci. 2013, 50, 90–96.
(29) Wang, J.; Yu, S.; Zhang, M.; Jin, W.; Huang, Z.; Chen, S.; et al. Burning velocity and statistical flame front structure of turbulent premixed flames at high pressure up to 1.0 MPa. Exp. Therm. Fluid Sci. 2015, 68, 196–204.
(30) Grover, J. I.; Fales, E. N.; Scurlock, A. C. Turbulent flame studies in two-dimensional open burners. Symp. Combust. 1963, 9, 15.
(31) Zhang, M.; Wang, J.; Xie, Y.; Jin, W.; Wei, Z.; Huang, Z.; et al. Flame front structure and burning velocity of turbulent premixed CH4/H2/air flames. Int. J. Hydrogen Energy 2013, 38, 11421–11428.
(32) Obando, J.; Lezcano, C.; Amell, A. Experimental analysis of the addition and substitution of sub-bituminous pulverized coal in a natural gas premixed flame. Appl. Therm. Eng. 2017, 125, 232–239.
(33) Rockwell, S. Influence of Coal Dust on Premixed Turbulent Methane–Air Flames; Worcester Polytechnic Institute, 2012.
(34) Cardona Vargas, A.; Amell Arrieta, A.; Arrieta, C. E. Combustion characteristics of several typical shale gas mixtures. J. Nat. Gas Sci. Eng. 2016, 33, 296–304.
(35) Tyagi, H.; Liu, R.; Ting, D. S.-K.; Johnston, C. R. Measurement of wake properties of a sphere in freestream turbulence. Exp. Therm. Fluid Sci. 2006, 30, 587–604.
(36) Gülder, Ö. L. Turbulent premixed flame propagation models for different combustion regimes. Symp. Combust. 1991, 23, 743–750.
(37) Cardona, C. A.; Amell, A. A. Laminar burning velocity and interchangeability analysis of biogas/CH3H/H2 with normal and oxygen-enriched air. Int. J. Hydrogen Energy 2013, 38, 7994–8001.
(38) Kee, R. J.; Rupley, F. M.; Miller, J. A.; Coltrin, M. E.; Grccar, J. F.; Meeks, E.; et al. CHEMKIN Collection, Release 3.6, 2000.
(39) Kee, R.; Grccar, J.; Smooke, M.; Miller, J.; Meeks, E. PREMIX: A FORTRAN Program for Modeling Steady Laminar One-Dimensional; SANDIA Natl Lab, 1985; pp 1–87.
(40) Smith, G. P.; Golden, D. M.; Frenklach, M.; Moriarty, N. W.; Etteneer, B.; Goldenberg, M.; et al. GRI-Mech 3.0, 2000.
(41) Vagelopoulos, C. M.; Egolfopoulos, F. N. Direct experimental determination of laminar flame speeds. Symp. Combust. 1998, 27, 513–519.
(42) Peters, N. Laminar flamelet concepts in turbulent combustion. Symp. Combust. 1988, 21, 1231–1250.
(43) Lasdon, L. S.; Waren, A. D.; Jain, A.; Ratner, M. Design and Testing of a Generalized Reduced Gradient Code for Nonlinear Programming. ACM Trans. Math Software 1978, 4, 34–50.