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EXPERIMENTAL STUDY OF THE CORRELATION FOR TURBULENT BURNING VELOCITY AT SUBATMOSPHERIC PRESSURE

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Abstract

Turbulent burning velocity is one of the most relevant parameters to characterize the premixed turbulent flames. Different correlation has been proposed to estimate this parameter. However, most of them have been obtained using experimental data at atmospheric pressure or higher. The present study is focused on obtaining a correlation for the turbulent burning velocity using data at sub-atmospheric pressure. The turbulent burning velocity was experimentally calculated using the burner method, where turbulent premix flames are generated in a Bunsen burner. Stoichiometric and lean conditions were evaluated at a pressure of 0.85 atm and 0.98 atm, whereas the turbulence intensity was varied for each condition. Perforated plates and a hot-wire anemometer were used to generate and measure the turbulence intensity. Schlieren images were used to obtain the average angle of the flame and calculate the turbulent burning velocity. Experiments and theory show that the turbulent deflagration rate decrease as pressure decrease. The turbulent deflagration speed decreased by up to 16 % at 0.85 atm concerning atmospheric conditions for the same turbulence intensity, discharge velocity, and ambient temperature, according to the experimental results. The comparison among the experimental results at sub-atmospheric conditions and the correlations reported in the literature exposes prediction issues because most of them are fitted using data at atmospheric conditions. A general correlation is raised between turbulent burning velocity (S_T), laminar burning velocity (S_L) and turbulence intensity (u') proposed from the experimental data. This correlation has the form $S_T/S_L \propto \alpha[u'/S_L]^n$. For sub-atmospheric and atmospheric conditions, the coefficients were determined.

Keywords: progress variable, subatmospheric pressure, theoretical correlation, turbulent burning velocity.

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1. Introduction

The turbulent burning velocity is one of the fundamental parameters to characterize a turbulent premix flame, due to the effect of pressure on the sensitivity of elemental chemical reactions, diffusive phenomena (thermal diffusivity and molecular diffusivity), the number from the integral scale, the thickness of the laminar flame front and the laminar burning velocity, this property has a great impact on the combustion process of industrial and domestic equipment such as boilers, combustion engines, gas turbines, among other.

The laminar burning velocity is a characterization parameter of a laminar premix flame since it provides physical-chemical information of the fuel mixture that allows the study and prevention of undesirable phenomena such as extinction, flame detachment, and back flame [1–3]. However, few combustion pieces of equipment operate under this regime, and on the contrary, many combustion pieces of equipment such as boilers, engines, gas turbines, and others operate under the turbulent combustion regime, so it is pertinent to deepen and study this topic.

Different studies have been carried out worldwide on the turbulent combustion of methane at atmospheric conditions of sea level and at elevated pressure and temperature conditions [4–7]. However, for subatmospheric conditions, there are few or no references and studies, this is mainly because in the world most of research centers have their facilities at sea level and also because a large part of the energy applications in the industrial and residential sectors in many countries are carried out at these atmospheric conditions.

In Latin America many important cities are located at high altitudes, La Paz (3719 masl), Ciudad de México (2240 masl), Quito (2850 masl) [8], and in the case of Colombia find cities such as Santa Fe de Bogotá (2600 masl) and Medellín (1550 masl) [8], which generates natural laboratories for experimentation at low pressure, that is, at pressures less than 1 atm, which in the literature is known as a subatmospheric condition. It is important to know how the combustion properties vary under these conditions, in this case, the study of the turbulent burning velocity, since combustion equipment such as boilers, internal combustion engines, turbines, operate under the turbulent combustion regime and are used in industry and transportation in Colombia.

The turbulent burning velocity is one of the fundamental parameters to characterize a turbulent premix flame, due to the effect of pressure on the sensitivity of elemental chemical reactions, diffusive phenomena (thermal diffusivity and molecular diffusivity), the Reynolds number on the integral scale, the thickness of the laminar flame front and the laminar burning velocity, and also the combined effect of these factors, it is then expected that with respect to the behavior of the turbulent burning velocity at atmospheric conditions (1 atm–1013 mbar), significant variations are present at sub atmospheric conditions (0.85 atm–849 mbar). This hypothesis is evidenced by the following analysis.

Many correlations between laminar burning velocity and turbulent burning velocity have been studied in general terms by different authors [9–12]. Studies have also focused on the study of methane and air premix flames, arriving at correlations for the turbulent burning velocity $S_T = f(S_L, u', P)$ as a function of laminar burning velocity, turbulence intensity and pressure.

The authors in reference [5] propose the following correlation, found experimentally for a range of pressures from atmospheric pressure to a pressure of 9.87 atm and the temperature of the mixture of 300 K and 573 K was measured by (1):

$$\frac{S_T}{S_L} = 5.04\left[\left(\frac{P}{P_0}\right)\left(\frac{u'}{S_L}\right)\right]^{0.38}, \tag{1}$$

where S_T is the turbulent burning velocity; S_L is the laminar burning velocity; u' is the intensity of turbulence; P is the premix pressure (range 0.99 atm to 9.87 atm), and P_0 is the reference pressure (0.99 atm).

From the above equation, the direct effect of the pressure of the premix on the turbulent burning velocity is observed, it is expected that when the pressure increases, the turbulent burning velocity will increase.

As observed in (1), the laminar burning velocity is a parameter that has a direct influence on the turbulent burning velocity, so this is an important starting point to perform turbulent burning velocity analysis. From the analysis carried out in reference [13], where an analytical expression is determined for the laminar burning velocity as a function of pressure, there is (2):

$$S_L \propto P^{(n-2)/2}, \tag{2}$$

where S_L is the laminar burning velocity; P is the premix pressure; and n is the order of the global reaction. And in this case for a global reaction for methane with order equal to 1, and supported by the (1), in a general way, it can be concluded that as the pressure increases, the laminar burning velocity decreases, as observed in (3).

$$S_L \propto P^{-0.5}. \tag{3}$$

Another important factor to consider in this experiment is that when changes in atmospheric pressure are generated, changes occur in the velocity field of the premix, and important variations may occur in the order of magnitude of the turbulence intensity of the premix, with which turbulent burning velocity may be affected.

The present study shows the methodology to determine the turbulent burning velocity, this is done for two pressure conditions, 0.98 atm corresponding to the atmospheric pressure of the city of Caucasia, and a pressure condition of 0.85 atm, corresponding to the atmospheric pressure of the city of Medellín, Colombia. Subsequently, with the experimental results, theoretical correlations are proposed for these pressure conditions.

One author mentioned in the work of reference [1] was one of the first to propose a turbulent flame theory. It should be noted that while the laminar burning velocity S_L is a physicochemical and chemical property of an unburned premix, the turbulent burning velocity S_T is a mass consumption rate per unit area divided by the density of the unburned premix. Therefore, S_T depends on the properties of the turbulent field in which it exists.

[9, 11] derived the first models of the turbulent burning velocity. Both researchers equalize the mass flow, m point, $\dot{m}$, through the cross-sectional area of a wrinkled flame, A_T, to mass flow through the area of a laminar flame of an unburned premix, A_L, (4). This model is based on the increase of the surface area due to the wrinkles of the flame by large turbulent eddies [11], where (5) is obtained.

$$\dot{m} = \rho_u A_T S_T = \rho_u A_L S_L, \tag{4}$$

$$\frac{S_T}{S_L} = \frac{A_L}{A_T}. \tag{5}$$

The authors in reference [9] proposed that the relationship between the area of the laminar flame and the cross-sectional area of the wrinkled flame can be approximated by (6):

$$\frac{A_L}{A_T} = \frac{S_L + u'_{rms}}{S_L} = 1 + \frac{u'_{rms}}{S_L}. \tag{6}$$

And substituting this result in (5), the result is (7):

$$\frac{S_T}{S_L} = 1 + \frac{u'_{rms}}{S_L}. \tag{7}$$

Other correlations presented by different authors of the turbulent burning velocity as a function of the laminar burning velocity and the turbulence intensity are shown in **Table 1**.

Table 1

Turbulent Burning Velocity Correlation

Equation	Reference	Equation number
$\frac{S_T}{S_L} = 1 + \frac{u'_{rms}}{S_L}$	[1]	(8)
$\frac{S_T}{S_L} = \sqrt{1 + \left(\frac{2u'_{rms}}{S_L}\right)^2}$	[1]	(9)
$\frac{S_T}{S_L} = 1 + \sqrt{\frac{2u'_{rms}}{S_L}}$	[1]	(10)
$\frac{S_T}{S_L} = 1 + C\left(\frac{u'}{S_L}\right)^n$	[2]	(11)
$\frac{S_T}{S_L} = 5.04\left[\left(\frac{P}{P_0}\right)\left(\frac{u'}{S_L}\right)\right]^{0.38}$	[3]	(12)

As can be seen, not all correlations consider the pressure effect on turbulent burning velocity and those that do, were tested using pressure equal to or higher than 1 atm. Therefore, the objectives of the present study are to analyze the effect of the subatmospheric pressure on the turbulent burning velocity at different flow conditions and provide a correlation obtained at sub-atmospheric pressure.

2. Materials and methods

2. 1. Turbulent premix Bunsen burner

Turbulent flames with a certain intensity of turbulence are generated by a premix Bunsen burner and for the equivalence ratio to be studied, the burner is shown in **Fig. 1**. The burner mainly consists of a lower inlet for the methane and air premix, in the upper middle part of the burner there is a plate for generating turbulence, then there is a refrigeration circuit to keep the inlet temperature of the premix constant. and not overestimate the turbulent burning velocity and avoid flashback phenomena, to control the temperature of the premix this measure before the burner with a thermocouple, this refrigeration circuit is isolated employing retainers to ensure that there are no infiltrations of water, and finally, there is the stabilizing mechanism of the turbulent flame, which consists of a circular ring of 0.5 mm around the discharge, where a non-premixed hydrogen flame is generated. The average flow velocity at the outlet of the burner port was controlled between 3 and 7 m/s to avoid back-flame and detachment phenomena. The inside diameter of the burner port (I.D.) is 10 mm, and the turbulence generator plates are located 42 mm downstream of the burner port outlet.

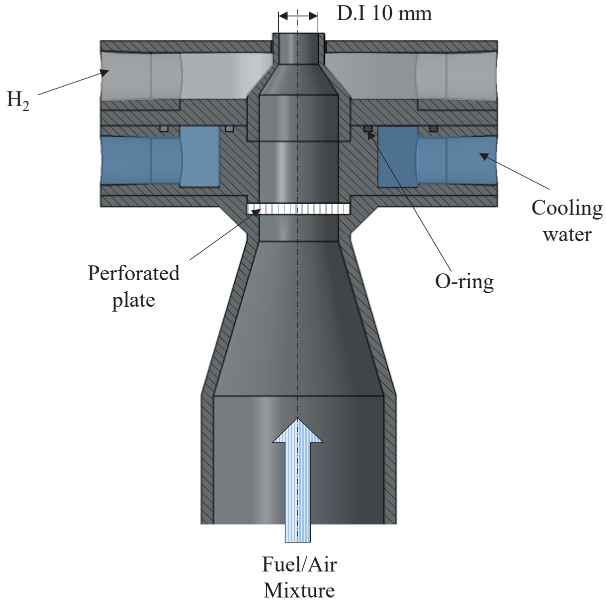


Fig. 1. Turbulent premix Bunsen burner

2. 2. Experimental Setup

The experimental setup to determine the turbulence intensity is shown in **Fig. 2**. The turbulence measurement is carried out cold (without combustion). It is assumed that the intensity remains constant when combustion occurs, consequently, the effects of combustion on turbulence when the flow field accelerates when passing through the flame is not considered, this technique is validated by results reported by other authors [5, 14, 15]. The complete system consists of the base and the test burner, then a one-dimensional probe of type 55P11 is located for the hot wire anemometer, this one-dimensional probe is located in a specimen holder type 55H21, then the miniCTA 54T42 module is located, the National Instrument data acquisition card (Hi-speed USB Carrier, NI USB9162), and finally there is an exclusive Dell brand computer for the experiment, where the programs are installed and the configuration of the data acquisition system is carried out.

Where the data is subsequently processed, and the turbulence intensity is obtained u'. For each condition, mixture, equivalence ratio, and intensity of turbulence, 2400000 were recorded at a frequency of 40 kHz. From the data taken for each condition, the mean flow velocity and turbulence intensity were calculated.

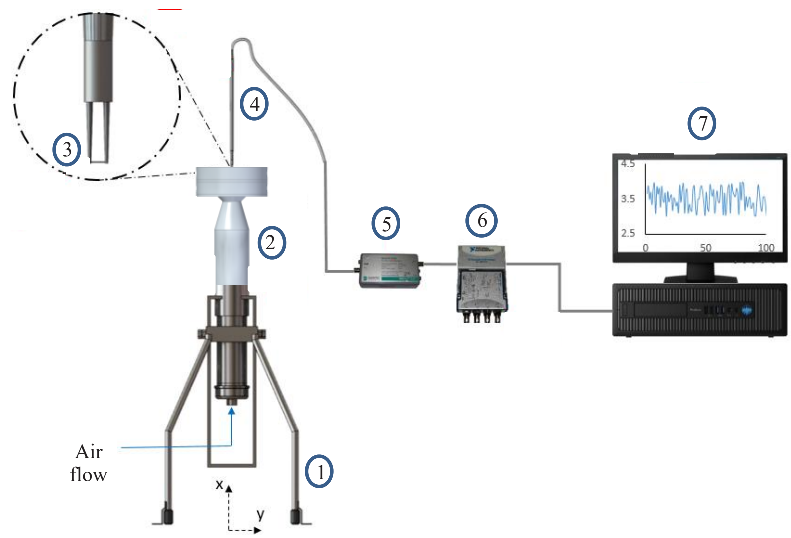


Fig. 2. Experimental setup to determine the intensity of turbulence:
1 – b base; 2 – burner head; 3 – hotwire probe (1D); 4 – probe holder; 5 – miniCTA module;
6 – data acquisition card; 7 – computer for data analysis

Schlieren measurements were made to identify the instantaneous flame front structure of the turbulent premixed flames. A scheme of the experimental setup is presented in **Fig. 3.**

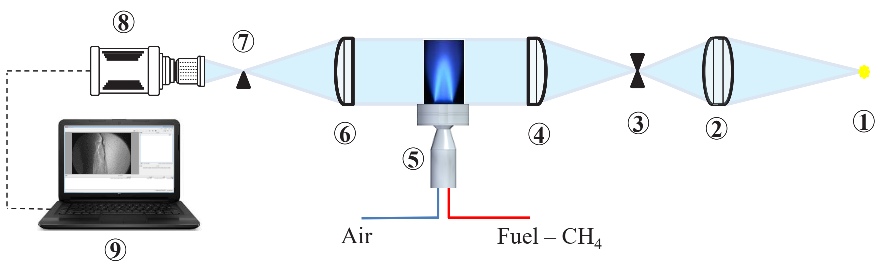


Fig. 3. Diagram of the experimental setup for the Schlieren technique:
1 – light source; 2 – biconvex lens; 3 – pinhole; 4 – plano-convex lens; 5 – turbo-slow premix burner; 6 – plano-convex lens; 7 – adjustable slot; 8 – CCD camera; 9 – computer

2. 3. Data acquisition and image processing

The data acquisition is achieved after establishing the equivalence ratio and the desired turbulence intensity, in this stage for each condition of the turbulent premix flame 60 images are captured, using the Schlieren technique, which is processed and the average flame angle.

After capturing the 60 images by means of a subroutine developed in the Matlab® software, the profile for each of the flames is obtained and then the average profile of these is obtained, to later determine the average angle of the flame.

Fig. 4 shows the analysis method for obtaining the average angle of the turbulent premix flames. (a) Turbulent premix flame at established conditions of equivalence ratio and turbulence intensity. (b) In Matlab® software the image is cropped and determines the profile of the flame, by selecting the profile, this selection was made manually following the methodology in references [16, 17]. The uncertainty associated with selecting the flame profile manually is not quantified in the current work. (c) Then convert the location of the flame from pixels to units of length. (d) This procedure is performed for 60 images and the flame profiles obtained are combined. (e) For the average image, the interior points (unburned premix) that correspond to a value for the progress variable $c = 0$ and the exterior points (burned gases) that correspond to a value for the progress variable $c = 1$ are determined (f) After combining the images, they are averaged to obtain a single profile and determine the average angle α of the 60 images, this average angle is determined using a value for the progress variable of $c = 0.1$ according to values referenced in the literature [5, 18] obtaining this angle was always possible for all the conditions of the experiment, and the error in the measurement of the angle is associated with the tolerance of the progress variable which corresponds to plus or minus 10 %.

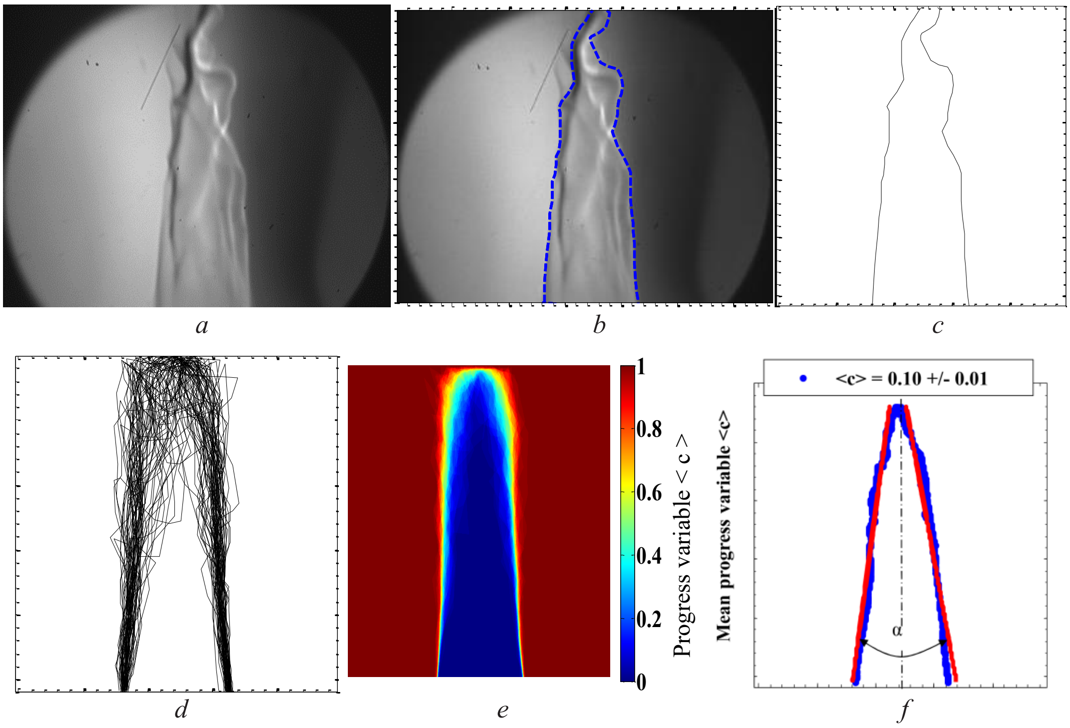


Fig. 4. Image processing of turbulent premix flames: *a* – Schlieren image; *b* – selection of the flame front contour; *c* – flame front contour; *d* – superposition of 60 flame fronts; *e* – progress variable; *f* – the average angle of the flame front

2. 4. Experimental Procedure

To carry out the experimental tests, turbulent premix flames are generated in a Bunsen burner for methane, for different turbulence intensities and the desired equivalence ratio, using rotameters calibrated specifically for each gas, the composition and equivalence factor is guaranteed. Of the methane-air premix, in addition, pilot flames are generated to sustain the flame. The burner port is kept cool so that the premix does not preheat and avoid back-flame phenomena and attenuate the effect of the temperature of the premix on the turbulent burning velocity. To determine the turbulent burning velocity, the angle method is used as shown in **Fig. 5**, which consists of determining the average angle of the flames and the average speed of the methane-air premix at the outlet of the burner port.

Once the average angle of the turbulent premixed flame has been determined, the average speed U of the methane-air premixed at the outlet of the burner port is determined, for this the (13):

$$U = \frac{Q_f + Q_a}{A_b}, \tag{13}$$

where U is the average speed of the premix at the burner port, Q_f is the on-site flow (calculated at the test site pressure and temperature conditions) of fuel in the premix at the pressure and temperature conditions, Q_a is the on-site flow rate (calculated at the test site pressure and temperature conditions) of air in the premix at the pressure and temperature conditions, and A_b is the burner port area.

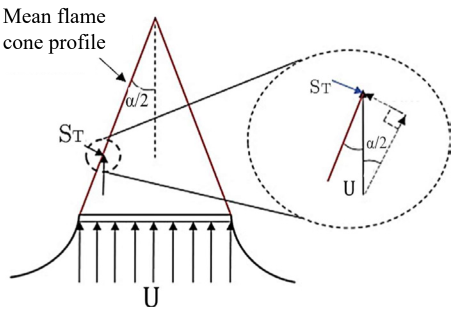


Fig. 5. Burner contour profile and angle method

When the flame angle and the average velocity of the premix at the burner outlet are correctly determined, the turbulent burning velocity S_T is determined by (14) as:

$$S_T = U \sin\left(\frac{\alpha}{2}\right), \tag{14}$$

where S_T is the turbulent burning velocity, U is the average speed of the premix at the burner port, and α is the angle of the premix flame front.

3. Results and discussions

3. 1. Turbulent burning velocity versus turbulent intensity

Fig. 6 shows the turbulent burning velocity versus the turbulence intensity compared with experimental results from [17, 19], as the results can be observed in the **Fig. 6**. Experiments at a pressure of 0.85 atm are generally less than for pressure of 0.98 atm.

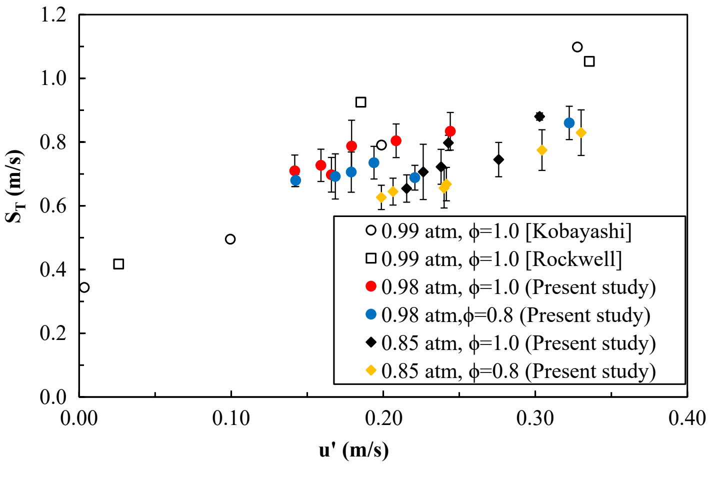


Fig. 6. Turbulent burning velocity versus turbulent intensity

The effects of pressure on the turbulent burning velocity show a trend since for the results obtained at a pressure of 0.85 atm lower results are obtained for the turbulent deflagration velocity concerning the results obtained at 0.98 atm, a decrease of up to 16 % of the turbulent deflagration speed is found at 0.85 atm concerning the close condition of sea level of 0.98 atm, for the same conditions of turbulence intensity, discharge velocity in the burner port, and ambient temperature.

3. 2. Theoretical correlations to determine the turbulent burning velocity

To make comparisons of the experimental results obtained in the present work, different theoretical correlations proposed by some authors are plotted. These correlations correspond to (8)–(10). Other authors (in (11)) using values for the constant $C = 1.6$ and $n = 0.3$, same as the doctoral work developed by [16]).

These comparisons are made for the two studied pressure conditions corresponding to 0.98 atm and 0.85 atm, and also for the two studied equivalence ratios corresponding to 0.8 and 1.0. As seen in **Fig. 7, 8**, no correlation fits the entire experimental data set.

By way of illustration, different points are compared for an equivalence ratio value and a pressure value:

For $\phi = 1.0$ and $P = 0.98$ atm (**Fig. 7, *a***).

For this condition, it is observed that the theoretical correlation that best adjusts to the experimental results of the present study is the correlation (10), and for the other correlations there is an overestimation or underestimation of the results.

For $\phi = 0.8$ and $P = 0.98$ atm (**Fig. 7, *b***).

The correlation called by other authors (11) presents a better approach to the experimental data in a range of turbulence intensity of 0.15 to 0.2 m/s, and the other correlations do not present a good fit.

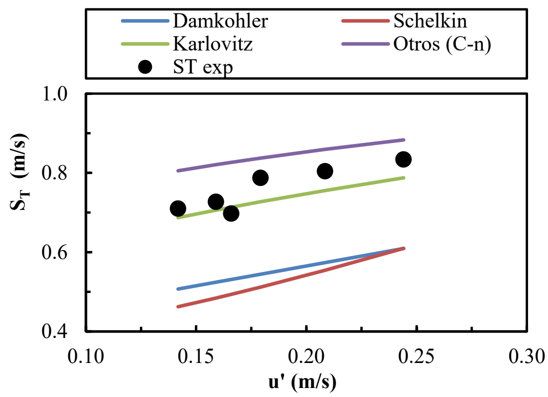
For $\phi = 1.0$ and $P = 0.85$ atm (**Fig. 8, *a***).

In this condition, the correlation (8) and the correlation (9) represent in a good way most of the experimental data, presenting small variations in their prediction, for the others correlations overestimate the results.

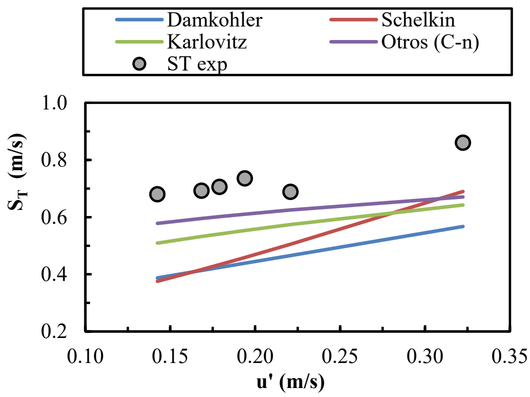
For $\phi = 0.8$ and $P = 0.85$ atm (**Fig. 8, *b***).

The correlation (10) presents a good fit in this specific condition in the range of turbulence intensity from 0.2 to 0.25 m/s.

As observed in these analyzes, no correlation correctly predicts the entire data set under the experimental conditions of the present study, these differences between the theoretical and experimental results may be due to specific conditions in the theoretical models as, for example, they are not valid for any pressure condition, they do not apply to any range of turbulence intensity and Reynolds number. This being an important point to propose theoretical correlations that fit the experimental data.

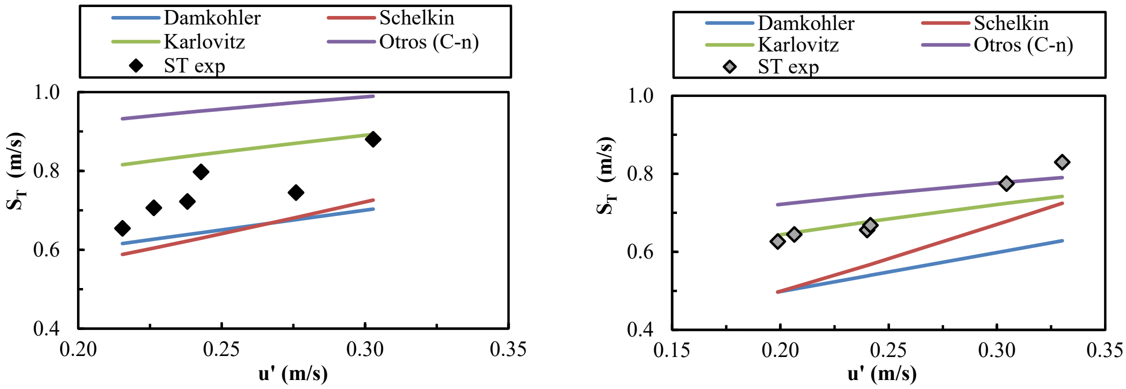


a



b

Fig. 7. Theoretical correlations and experimental data of the present work for the turbulent burning velocity at 0.98 atm and 297 K: $a - \phi = 1.0$; $b - \phi = 0.8$



a *b*

Fig. 8. Theoretical correlations and experimental data
of the present work for the turbulent burning velocity at 0.85 atm and 297 K:
a – ϕ = 1.0; *b* – ϕ = 0.8

3. 3. Proposed Correlation for Turbulent Velocity

The relationship of S_T/S_L and u'/S_L is used in previous turbulent combustion studies [5, 20] for comparative purposes. u'/S_L indicates information about turbulent flow and laminar flame, on the other hand S_T/S_L indicates information about the turbulent flame and the laminar flame. **Fig. 9** shows the variation of S_T/S_L with u'/S_L. As seen in the **Fig. 9** S_T/S_L increases directly with increments of u'/S_L. In previous studies some correlations have been proposed in a general way such that S_T/S_L be a power function of the turbulence intensity u'/S_L [15, 21]. This function has the form of (15).

$$\frac{S_T}{S_L} \propto \alpha \left[\frac{u\prime}{S_L}\right]^n. \tag{15}$$

In this study, a similar correlation arises for methane at two conditions of pressure and equivalence ratio. As it's shown in the following. **Fig. 9** presents the correlation for a pressure condition of 0.98 atm and equivalence ratios of 0.8 and 1.0. While **Fig. 10** is a correlation for pressure of 0.85 atm and equivalence ratio of 0.8 and 1.0.

Similar studies in the literature [22] present the turbulent burning correlation, this correlation presented a relation between pressure and turbulent intensity. In the present work, the turbulent burning velocity relation is presented by turbulence intensity dependence. In this case for the relation presented in **Fig. 9, 10** the error between the experimental data and the turbulent burning correlation proposed was below 15 %.

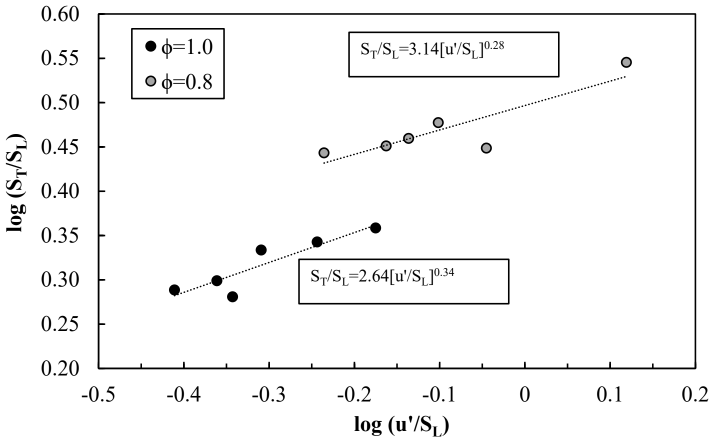


Fig. 9. Turbulent burning velocity correlation S_T/S_L y u'/S_L for the mix CH_4/air
at 0.98 atm and 297 K

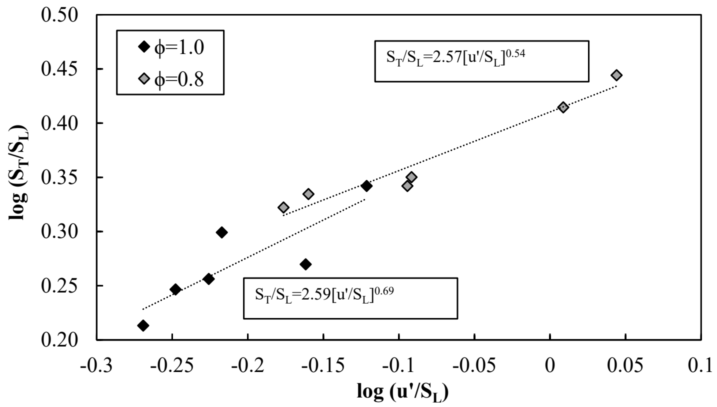


Fig. 10. Turbulent burning velocity correlation S_T/S_L y u'/S_L for the mix CH_4/air at 0.85 atm and 297 K

From these results, reliable ranges of operation of combustion equipment operating at heights above sea level corresponding to atmospheric pressures of 0.85 atm and 0.98 atm were determined, these results are important when it is necessary to design atmospheric burners for different industrial processes and domestic, in addition, these results are a fundamental basis for future studies on turbulent burning velocity in subatmospheric conditions. These results also provide a reliable database for future work on combustion engines, where to perform numerical simulations, it is essential to know the values of turbulent burning velocity. In future work, it is important to analyze more subatmospheric pressure conditions and have a greater base for the different applications in combustion equipment.

4. Conclusions

As a general conclusion, with the study, carried out, behaviors are appreciated that give rise to proposing future approaches that help to broaden and deepen issues related to the stability ranges of flames in turbulent regime with different pressure changes, in addition, the theory shows that the turbulent burning velocity increases as pressure increases, the same behavior is presented for turbulence intensity, and this behavior is reflected in the experimental results obtained. During the execution of this work, an experimental methodology was developed to determine the speed of turbulent burning at different conditions of pressure, equivalence ratio, and intensity of turbulence, this experimental methodology was validated by comparing it with experimental results reported by other authors, and in general, it was it must be for this type of experimental setup it is not possible to control the intensity of turbulence since it is affected by pressure. A general correlation is raised between S_T/S_L y u'/S_L proposed from the experimental data obtained in the two conditions of equivalence ratio and pressure, this correlation has the form $S_T \big/ S_L \propto \alpha\left[u\prime/S_L\right]^n$, for the pressure of 0.98 atm the correlation constants are $\alpha = 2.64$, $n = 0.34$, and $\alpha = 3.14$, $n = 0.28$, for $\phi = 1.0$ and $\phi = 0.8$, respectively. For the pressure of 0.85 atm the correlation constants are $\alpha = 2.59$, $n = 0.69$, and $\alpha = 2.57$, $n = 0.54$, for $\phi = 1.0$ and $\phi = 0.8$, respectively.

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