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# LAMINAR FLAME SPEED MEASUREMENTS OF NATURAL GAS / AIR MIXTURES USING A FLAT FLAME BURNER

**Roberto Wolf Francisco Jr.**
**Alana Heil**
**Amir Antônio Martins de Oliveira Jr.**
Federal University of Santa Catarina, Mechanical Engineering Department, Florianópolis, SC, Brazil.
Email: roberto@labcet.ufsc.br

***Abstract.*** *The objective of this work is to measure the laminar flame speed of natural gas, which consists of light hydrocarbons, predominantly methane, premixed with air using the flat flame burner method. A McKenna flat flame burner with a water cooled stainless steel porous plate was used in this work. Flames at different mean flow velocities are stabilized at different heat transfer rates to the water flow. The intercept at zero heat transfer rate provides the adiabatic laminar flame speed. The direct shadowgraph method provides and upper limit for the curve fitted region. The measured values of flame speed were compared to other similar measurements from the literature and to predictions using the GRIMECH 3.0. The measurement uncertainty was estimated and within the uncertainty range a good agreement was found.*

***Keywords:*** *laminar flame speed, natural gas, flat flame, shadowgraph.*

## 1. INTRODUCTION

Natural gas is a fuel that is gaseous at ambient conditions of temperature and pressure, found in nature as a diverse mixture of hydrocarbons whose main component is methane. Composition, however, varies according to natural factors that determine its formation process. Found in underground reservoirs, such as petroleum, natural gas often is found associated with petroleum and its composition has greater quantities of ethane, propane, butane and heavier hydrocarbons, while the natural gas not associated with petroleum (or low amount of it) has a higher methane content. Apart from hydrocarbons, $CO_2$, $N_2$, $H_2S$, $H_2O$, HCl, methanol, and other impurities are also part of its composition.

To be marketed it undergoes a treatment which makes removal of impurities and the separation of heavy hydrocarbons, resulting predominantly methane, in order to meet specifications recommended by technical standards.

Even so, the composition is flexible and continues with a variety of proportions, it depends on where the fuel will be applied. Commercial natural gas compositions vary from 70% to 95% CH4, with the balance composed of heavier hydrocarbons (McTaggart-Cowan, 2010).

Natural gas is frequently used for heating, cooking, manufacture of plastics, fertilizers, electricity generation and also as a fuel for vehicles, as an alternative to gasoline. Despite being a fossil fuel is less polluting than petroleum and coal, and due to its high calorific value, around 95kcal/m3, and high energy efficiency is considered a good quality fuel. Natural gas has attracted attention in recent years due to the various advantages it possess, which enables the development of various technologies relating to their use and technological innovations in industrial equipment. Fuel characteristics such as laminar flame speed are desirable properties to develop combustion strategies and evaluate dynamic stability.

Studies on alternative fuel has become one of the most important ways to solve energy shortages and environmental pollutions (Gu, 2011). Laminar burning velocity, which is a fundamental characteristic of the mixture, has an important role in engine design and can validate the development of chemical combustion mechanism (Bradley, 1998; Jhon, 2010).

There are a number of techniques to measure the flame speed of gaseous fuels. The most commonly used methods are the constant volume, constant pressure, the opposed jet flame, the flat flame (with the heat flux method), and the conical flame [3-17]. Here, the flat flame method of Botha and Spalding [23] was chosen for measuring the laminar flame speed. The procedure developed allowed to reduce some of the associated uncertainties.

Thus, the objective of this work is to measure the laminar flame speed of natural gas, which consists of light hydrocarbons, predominantly methane, premixed with air using a McKenna flat flame burner. The shadowgraph method was used to evaluate the shape of the flame front and to establish an upper limit for the laminar flat flames. The uncertainty in the measurements was evaluated and measured flame speeds were compared to values reported in the literature for methane [18-20], since natural gas has very varied compositions and the results depend directly on the amount of methane present in the mixture. The chemical kinetic mechanisms GRIMech 3.0 [22] was used and the predictions were compared to the measured values.

## 2. EXPERIMENTAL SETUP

Figure 1 shows a schematic drawing of the McKenna flat flame burner used in this work. It was provided by Holthuis & Associates (http:// flatflame.com). The burner surface is divided into two separated porous layers. The inner region receives the reactant mixture that burns stably as a surface flame. The outer region receives a nitrogen flow that acts as a flow curtain isolating the ambient air from rich flames (Ø > 1).The nitrogen flow was turned off in the measurements that follow.

The porous plate over which the flame stabilizes is made of sintered stainless steel AISI 316. The measurement of the pressure drop as a function of volumetric flow rate of air in the range of the flow rates used in this work provided a straight line, clearly within the Darcy flow regime.

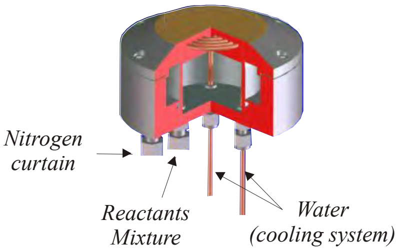

Figure 1. Schematic drawing of the McKenna burner used in this work (Adapted from http://flatflame.com/).

The permeability obtained was $3.3\times10^{-12}$ m$^2$. This permeability allowed estimating an order of magnitude of pore size of 3.2 ± 0.3 µm. The pore Reynolds number for the maximum Darcy velocity measured in this work, using air properties evaluated from 300 K to 600 K, varied from 0.060 to 0.018, well within the Darcy regime. This porous plate has a heat exchanger imbedded in it (Fig. 1) that allows for cooling and measurement of the heat transfer rate removed from the flame. Also, instabilities generated at the flame at higher flow velocities resulted in flame wrinkling. The direct shadowgraph was used to detect the higher limit for mean flow velocity. These will be explained in the next section.

Figure 2 shows a schematic drawing of the experimental setup used in this work. In the direct shadowgraph method used (Settles, 2001), the LED light projects the shadow of the flame front in a white background, and the image is captured by a photographic camera (Sony WX7 - 16.1 MP). The distance between the white background and the LED light was 800 mm, with the burner positioned at the midway. With this setup, the projected image was twice the size of the flame itself.

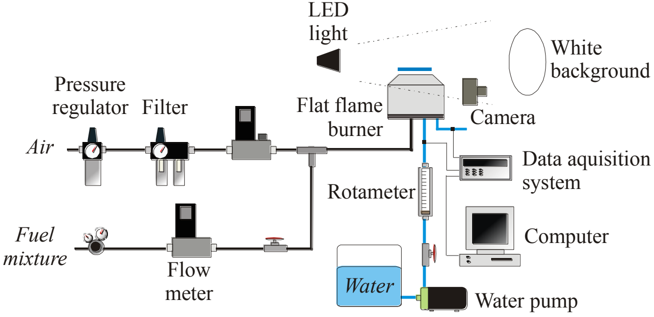

Figure 2. Schematic diagram of the experimental setup used in this work.

In this type of experiment, the greatest source of error is the measurement of flow rates, which affects the mean flow velocity and the fuel composition, when it is regulated from independently controlled gas lines. Here, care was taken to reduce these possible sources of measurement uncertainties. The volumetric water flow rate was measured with a rotameter calibrated at the beginning of each experiment with a precision balance and kept fixed at 0.3 slpm throughout the experiments. To allow for the measurement of the heat transfer rate to the water, the water temperature was measured with type K thermocouples (chromel/alumel) positioned approximately 30mm before the inlet and after the outlet of the burner's cooling system. The thermocouples were connected to a data acquisition system (Agilent - 34970A) interfaced with a computer.

The fuel supply system was composed of bottled gases, a flow meter (Omega Engineering, Inc. - Model FMA 1824, range 0-20 slpm), the control was made with the use of a needle valve for adjusting the gas flow. The natural gas used was composed of: 88.985% $CH_4$, 6.037% $C_2H_6$, 1.986% $C_3H_8$, 1.2% $N_2$, 1.036% $CO_2$, 0.467% n-$C_4H_{10}$, 0.292% i-$C_4H_{10}$.

The air supply system was composed of an alternative compressor connected to a storage tank, a pressure regulator, a filter, a reducing valve and a flow meter/controller (Omega Engineering, Inc. - Model No. FMA-773A-V, range 0-50 slpm. During the tests, the air pressure at the line was kept at 2.0 bar (gauge), while the burner operated under atmospheric pressure.

Based on this setup and the measurement procedure to be explained below, from an error propagation analysis, the maximum experimental uncertainties at the equivalence ratio and mean flow velocity are ± 0.05 and± 2.0 cm/s, respectively. The unburned mixture mean flow velocity, $u_{fl}$, is defined as the volumetric flow rate of reactants divided by the transversal sectional area of the burner. We note that the uncertainty related to the heat transfer rate, ± 2 W, arises from the uncertainty in the temperature measurement(± 1.0 K), and from the estimate of the heat loss to the external ambient (0.5 % of the burner power).

## 3. EXPERIMENTAL PROCEDURE

It was observed that for each equivalence ratio (Ø), the flame front underwent a transition from a flat to wrinkled flame at a given unburned mixture flow velocity ($u_{fl}$). Mean flow velocity above this transition make the wrinkle increase, and when mean flow velocity is continuously decreased below this transition, instabilities begin to appear at the edges, grow, until the extinction occurs. Figure 3 shows photographs of the (a) flat flame front and (b) the wrinkled flame. Both mean flow velocity shown are actually lower than the laminar flame speed because they were affected by heat loss to the burner. It is noticeable that the transition from the flat to the wrinkled regimes happens at flame velocities values whose difference is on the same order of magnitude as the measurement uncertainty.

The critical velocity separating the wrinkled from the flat flames was defined as the upper limit for measurement (ULM). The lower limit for measurement (LLM) was determined by the extinction.

(a) (b)

Figure 3. Pictures of the flame front obtained for premixed methane and air, with heat loss. (a) The flat flame and (b) the wrinkled flame.

In order to use a standard method to define the ULM, mostly independent from the operator, a MATLAB (Version 7.9.0) routine was written to measure the amount of wrinkling. For this analysis, first the direct shadowgraph images were taken for different average flow velocities, as shown in Fig. 4. Using MATLAB, the image was converted to shades of gray and the region of interest for analysis was selected. The red line shown in Fig. 5 represents the region of interest selected.

(a) (b)

Figure 4. Projected image of the flame front shown in Fig. 3, obtained with the direct shadowgraph method, for (a) the flat flame and (b) the wrinkled flame.

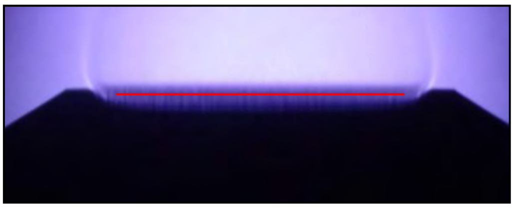

Figure 5. Region of interest selected for image analysis using MATLAB.

A graph of pixel intensity versus length along the flame front was drawn. The pixel intensity was normalized to vary between 0 and 256, for pixels completely black to completely white, respectively. The routine then calculated the standard deviation and the maximum and minimum values of pixel intensity. Here, the parameter of interest was the standard deviation (σ) and the flame front was considered flat when this parameter was smaller than 10.

The laminar flame speed was then obtained from measurements varying the unburned mixture averaged flow velocity from the LLM to the ULM. The flames were considered in steady-state when the temperatures of the water flow remained constant for at least 20 min. Recall that the water flow rate was kept always constant at 0.3 slpm. Then, the heat transfer rate from the flame front to the water of the cooling system was determined by the temperature difference from the inlet to the outlet water flow. From a plot of mean flow velocity versus heat transfer rate, the best fit line was extrapolated to zero heat transfer and the intercept provided the laminar flame speed. Mostly important, the accuracy of the heat transfer rate extrapolation was independent of the accuracy of the measurement of the water flow rate, as long as it was kept constant.

## 4. RESULTS

The experimental setup and procedure were validated measuring the laminar flame speed for methane premixed with air according with the work published in *6º European Combustion Meeting* (Francisco et al., 2013), in which testes were made for equivalence ratio between 0.8 and 1.2 using the shadowgraph method for analyzing the flatness of the flame. For all results shown below, the standards deviations obtained were lower than 10, in other words, the flame was actually flat.

Figure 6 shows the mean flow velocity as a function of heat transfer rate of water. It should be emphasized that the behavior of the heat transfer rate to the water flow is a result of two competing effects. As the flow velocity decreases, (1) the flame front approaches the burner surface increasing the heat transfer rate to the water flow and, (2) the thermal power delivered by the flame decreases, reducing the heat transfer rate.

From Fig. 6 (Ø = 1.0) is possible to observe that, initially, the first effect dominates. However, as the flame approaches the burner surface, the second effect becomes dominant. For velocities smaller than this value, instabilities grow at the flame front edges. If the flow velocity is reduced further, the flame front area decreases and extinction occurs. Thus, for each equivalence ratio, the value of mean flow velocity for which there is the inflection showed in Fig. 6 is associated to the LLM.

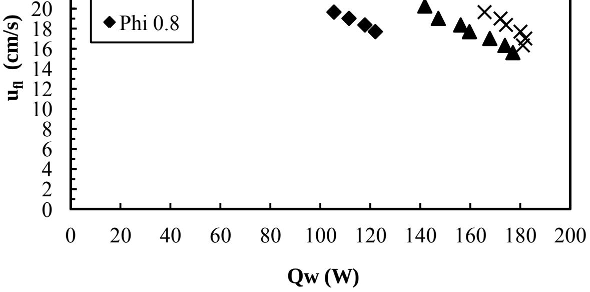

Figure 6. Mean flow velocity as a function of heat transfer rate to the water, for natural gas and air premixed.

The laminar flame speed was determined for the equivalence ratios between 0.8 and 1.0 by extrapolating the heat transfer rate for zero. Figure 7 presents the mean flow velocity as a function of the heat transfer rates to the water, for values of mean flow velocity between the LLM and ULM. For each curve fitted line the correlation coefficient $R^2$ is also shown.

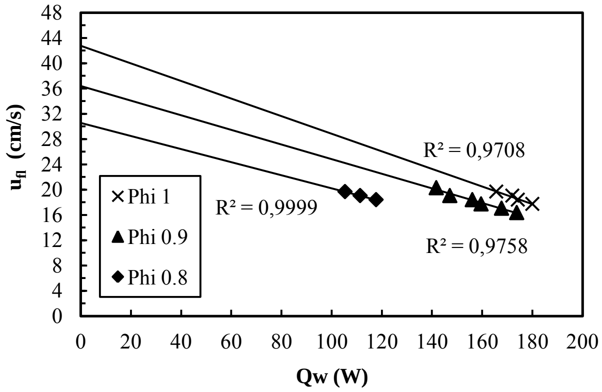

Figure 7. Extrapolation of the flow velocity to zero heat transfer using a natural gas, for equivalence ratio between 0.8 and 1.0.

A graph relating laminar flame speed ($S_l$) obtained for natural gas as a function of equivalence rate is shown in Fig. 8. The measurement uncertainties in the flame speed are presented the vertical error bars. The results were compared with flame speeds obtained with the methane and published by Bosschaart et al. (2004), Wang et al. (2012) and Mazas et al. (2011). As well as the predictions made with GRIMech 3.0 using both, natural gas (90% of methane) and pure methane.

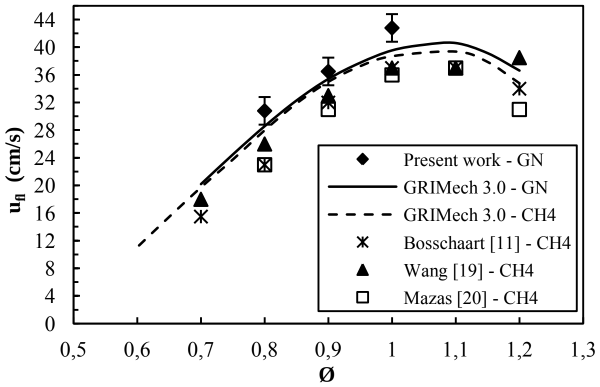

Figure 8. Laminar flame speed of natural gas premixed with air, for equivalence ratios between 0.8 and 1.0.

Natural gas presents values of flame speed higher than the flame speed of methane. However, it is possible to observe that the same tendency occurred with the results calculated using the GRIMech 3.0 for natural gas and methane. Furthermore, comparing the flame speed obtained experimentally and using the GRIMech 3.0, both for natural gas, it can be seen that the major difference was obtained for equivalence ratio equal 1.0. Table 1 shows the percentage difference between the laminar flame speed measured in this work and the results showed by other authors and those obtained using the GRIMEch 3.0.

Table 1. Percentage difference between the laminar flame speeds measured in this work $S_l$ and the values measured by other authors and calculated using GRIMech 3.0.

| Ø | $S_l$, [cm/s] | Bosschaart [2004] | Wang [2012] | Mazas [2011] | GRIMech 3.0 (methane) | GRIMech 3.0 (natural gas) |
|---|---|---|---|---|---|---|
| 1.0 | 42,8 | 15,68% | 15,68% | 18,89% | 10,68% | 8,27% |
| 0.9 | 36,5 | 14,06% | 10,61% | 17,74% | 4,38% | 3,08% |
| 0.8 | 30,8 | 33,91% | 18,46% | 33,91% | 10,16% | 7,81% |

The laminar flame speed for the stoichiometric mixture was found as 42,8 cm/s. The highest percentage difference of 18,89% when compared to Mazas´s result for methane. The kinetic model used proved satisfactory for natural gas, charging a maximum error of 8.27%.

## 5. CONCLUSIONS

A McKenna burner was used to measure laminar flame speeds natural gas, which consists of light hydrocarbons, predominantly methane, premixed with air using the flat flame burner method. The mean flow velocity and the heat transfer rate to the burner are then measured. Extrapolation for zero heat transfer rate provides the laminar flame speed. The major source of uncertainty is the measurement of volumetric flow rate of fuel and air. An error propagation analysis reveals uncertainties of ± 0.05 for the equivalence ratio and ± 2.0 cm/s for the mean flow velocity.

The measurements were compared to the values measured by Bosschaart et al. (2004), Wang et al. (2012), Mazas et al. (2011), and with predictions using GRIMech 3.0. The kinetic model used to predict the measurements showed good agreement.

The burner used and the procedure developed allowed the measurements within the range of interest. This is an ongoing project. Measurements for preheated methane at different equivalence rations are under way.

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