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OPTICAL LASER DIAGNOSTICS AND CHEMICAL KINETICS INVESTIGATION OF LAMINAR FLAME SPEED FOR HYDROUS ETHANOL

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Abstract. *The majority of Brazilian passenger vehicle fleet consists of flex fuel engines, which operates with gasoline (E25) and hydrous ethanol. Recently, the advance of computational fluid dynamics simulation applied on design of internal combustion engines (ICE) has highlighted the need of reliable chemical kinetics models for most common fuels applied on ICE operation, such as ethanol, gasoline and blends. Therefore, the mainly motivation for this study is determine and evaluate the influence of the water content on ethanol flames for laminar flame speed and chemical kinetics. Therefore, laminar flame speed measurements by OH-Emission and OH-Planar Lased Induced Fluorescence (PLIF) were conducted on anhydrous and hydrous ethanol premixed flames at atmospheric pressure. Distinct fuel samples were evaluated at several equivalence ratios. Chemical kinetic simulation considering Marinov´s mechanism was performed in order to match velocities obtained from experimental data versus values obtained through numerical simulation, and to verify the characteristics of hydroxyl production at conditions studied. A sensitivity analysis for defined species were performed for the test conditions and the images obtained by optical techniques were correlated to simulated cases.*

Keywords: *ethanol laminar flame speed; premixed burner; OH-PLIF; emission; chemical kinetics*

1. INTRODUCTION

Air pollution, greenhouse phenomena, depletion of oil resources, and its consequent price increasing, are some of the most common reasons entailing less petroleum based fuel consumption. Researches on alternative and clean sources of energy, as well as the investments on this field have risen during the past few years, being supported by universities and by industry.

Ethanol has become an attractive alternative fuel due its potential characteristics for substituting the most common applied fuels in spark ignition (SI) engines, such as gasoline. In addition, interest on ethanol has raised due to its green advantages to environment, as well as, its intrinsic characteristics, such as low heat value and high octane rate.

Furthermore, both fuels – gasoline-ethanol and hydrous ethanol – can be found in many blend proportions. In Brazil hydrous ethanol has been applied as an alternative fuel to gasoline in vehicles since 90’. Besides, it is applied as a gasoline-blending agent, achieving the proportion of 25% weight, in Brazilian market.

Its application in internal combustion engines (ICE), for example can be justified due to its attractive potential effects on performance and emissions without drastic design changes are required. In addition, the distribution chain (gas stations) is similar to gasoline (Bayraktar, 2005). Thus, the application and commercialization does not require a specific development and investment for distribution to consumers, instead of hydrogen or electric sources for example, which do not have large or economically feasible distribution chains. Moreover, in case of internal combustion engines the same hardware can be used, with some modifications, such as calibration and some specific features and parts. Nevertheless, studies related to its burning characteristic are not still widely investigated, so its application in a variety of internal and external combustion systems has not yet achieved the full potential it could, or its state of the art.

These leading goals for both energy security and clean air project are fundamental for attending the emission regulations targets, which became more restrictive during the past few years for automotive industry. Emissions associated to CO2, NOx and its effects on environment are associated with oil derived fuels consumption, mainly in vehicles.

Based on data from Renewable Fuels Association (2015) had shown that Brazil lost the leadership for ethanol production to USA since 2007. Although, it is important to emphasize that Brazil is still the main global player when ranking for sugarcane based production, as long as USA ethanol production is based on corn agriculture. Also, the Brazilian production costs are around 39% lower than USA, and the production per land unity is 45% higher than US (Archer and Szklo, 2016)

Moreover, it can be observed that total production has doubled in the last 8 years, strengthening the global interest on renewable sources of energy. Figure 1 presents the global ethanol production by country brought up by Renewable Fuels Association, considering data from 2007 until 2015. The major producer is USA – which ethanol production is based on corn agriculture – followed by Brazil – which production comes from sugarcane (Moore et al, 2011).

2. ETHANOL: ANHYDROUS OR HYDROUS?

Laminar flames speeds for numerous fuels have been studied and determined extensively by literature, for example: methane, propane, butane, ethanol and isooctane. Nevertheless, for hydrous ethanol there is still lack of reliable data available.

Ethanol production process includes the formation of feedstock, processing of the wort, followed by fermentation, distillation and dehydration. After fermentation, the resultant mixture contains alcohol, dead microbes, impurities and water. In order to produce ethanol fuel, the excess of water must be extracted, which is done by distillation. As hydrous ethanol is an azeotropic mixture, by this process the best that can be produced is fuel with 95.57%. For removing the remaining water further process are needed, making the fuel mixture produced too much expensive for consumer, justifying the largely usage of E96W4 in automotive industry for example.

The reason for studying hydrous ethanol is related to the difficulty and high costs involved in obtain the anhydrous fuel for large production and application. This way, for ICE in Brazil for example the regulations for its commercialization as fuel determines that it can contains at most 4.9% of water in volume (ANP, 2011).

According to Alternative Fuels Data Center (Renewable Fuel Association, 2015), the application of E85 in flex fuel vehicles, on North America fleet has increased 10 times, from 2000 up to 2010. In addition, the increase of total alternative fueled vehicles has increased by three times. Surely, this was a result of the lately more restrictive emission legislation pushing automotive industry towards a more efficient and clean energy application.

In addition, some authors have indicated gains in performance and emissions when water is added to fuel. Brewster et al (2007) evaluated engine performance in response to varying water contents of ethanol fuel. These blends were tested in a multi cylinder turbocharged SI engine with a centrally mounted spray guided direct engine. Part of their conclusions related the reducing in burning rate to the increasing of water content, leading to an ignition timing advance and increase in fuel flow. Besides that, it is observed a decrease in engine emissions of NOx and increase in HC, and due to its anti-knocking characteristics, a higher potential for increase in compression ratio and in output. However, it is important to emphasize that as water content raises; the operating conditions for engines are sensible deteriorated (Breaux, 2012).

The lack of experimental data available for ethanol flames is pointed as one of the causes for jeopardizing the combustion prediction on engine simulation codes. Therefore, the goal of this research work was to evaluate the properties for four ethanol samples containing water in a 0% to 15% content in mass. First, characteristics such as density, heat value and alcoholic percentage are presented. Then, LFS for each mixture is evaluated for distinct equivalence rates using a Bunsen burner at initial pressure of 1atm and 368K. Ethanol is vaporized using a specific apparatus and pre-mixed mixtures are obtained before reach the Bunsen burner, as it will be detailed in forward session. Applying OH-PLIF and OH-Emission, the reaction zones are recorded through an image intensifier coupled to a CCD camera and laminar flame speed is estimated based on cone area methodology (Glassman, 1987; Heywood, 1988).

3. LAMINAR FLAME SPEED

Laminar flame speed is one of the most important characteristics of any combustible mixture. Its dependency on pressure, temperature and equivalence ratio is well known. The burning velocity can be defined as the relative velocity, normal to the flame front, with which the unburnt gas moves into this front in adiabatic conditions. Determination of laminar burning velocity is fundamental for validation of chemical reaction mechanisms and to support a better understanding of the turbulent combustion process in spark ignition engines and power generation systems. This fuel property determines how fast the mass of fuel will be burned in the cylinder. A high flame speed reduces the time required for complete combustion, which produces lower exhaust temperatures, higher engine efficiency, and lower tendency to knock.

Broustail et al (2011) studied the LFS versus equivalence ratio for butanol/iso-octane-air and ethanol/ iso-octane-air mixtures, determining them experimentally through a spherically expanding flame methodology. These results showed the need of kinetics mechanisms development to predict laminar burning velocities for alcohol blended fuels and the importance of having experimental data for higher pressures and temperatures in order to better correlate the CFD modeling of ICE and improve the kinetic scheme applied in those softwares.

According to Vancoille (2012), turbulent combustion model used in predictive engine codes tracking the progress of the flame front trough the cylinder, usually adopts a fast chemistry approach, or flamelets regime. This way, the contribution of chemical reactions comes from laminar burning velocity, and turbulent influence is related to flame stretching and increase of flame front area. In their research various kinetic mechanisms were studied under distinct ranges of pressure (5-85 bar), temperatures (400-900K) and equivalence ratios (0.5-2.0), or engine like conditions.

Naucler et al (2012) has presented results for ethanol oxy-fuel combustion, where an oxidizing mixture composed by artificial air, O_2 and CO_2 is pre-mixed with fuel vaporized. The importance of studying oxy-fuel combustion is due to its capability of capturing CO_2 pathway. Besides, this sort of combustion has shown additional benefits of reducing NOx formation, contributing to lower emissions indexes. The flames were stabilized on a perforated plate burner, at atmospheric pressure, and the equivalence ratios studied were in the range of 0.5-0.7. Konnov´s mechanism was implemented in CHEMKIN, and then used for measurements validation. The comparison between experimental and simulated data presented a satisfactory agreement and the results obtained were relevant to future researches in this area.

Liao et al (2007) have focused their study on the effects of initial temperatures and on distinct fuel/air ratios on the laminar burning velocities of ethanol-air flames. A combustion bomb was used and spherically expanding laminar premixed flames were captured applying a high speed CCD, under various equivalence ratios and initial temperatures. It was observed that the increasing in initial temperature leads to a proportional rising in flame speeds. On the opposite way, when pressure is risen, the speeds tend to decay.

Augoye and Aleiferis (2015) published a study about flame growth comparing distinct fuels: gasoline, iso-octane, anhydrous ethanol and two sample for hydrous ethanol (E96W4 and E90W10). They used an optical engine operating in direct injection (DI) and indirect injection (or port fuel injection–PFI) configuration. Parameters such as heat release rate, indicated mean effective pressure (IMEP), burning duration, and pressure curves were obtained and used in correlating the OH-PLIF images obtained from flame development. As expected it was observed that the alcohols fuels burned faster than hydrocarbons fuels for both operations PFI and DI. Moreover, DI operation recorded slower burning rates than PFI configuration. The OH fluorescence presented more intensity and areas were generally higher for anhydrous ethanol, when compared to hydrous images samples, and the last presented more cyclic variability. Also, OH images for anhydrous are more well defined, in terms of edges than the samples with water, which showed a slightly distortion on their limits.

4. EXPERIMENTAL SETUP

The research conducted used two techniques for reaction zone acquisition: OH emission and OH Planar laser induced fluorescence (PLIF) applied to the flame resulted from a Bunsen burner apparatus.

4.1 Bunsen Burner and Fuel Vaporizer Configuration

A schematic of the experimental apparatus used for fuel vaporization can be seen in Figure 1, at left. The temperatures for fuel vapor and air+O_2 are constant. Pressure and flow for pre-heated ethanol is controlled by device indicated. Nitrogen flow is used in fuel reservoir to guarantee the constant fuel flow into the system.

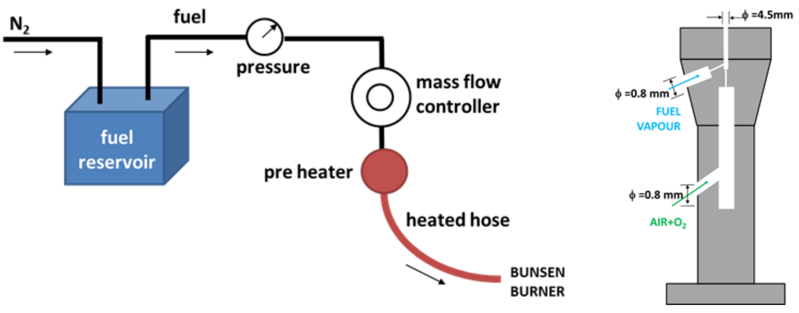


Figure 1. At left, diagram for fuel vaporizer device applied for the experiment. At right, Bunsen burner diagram.

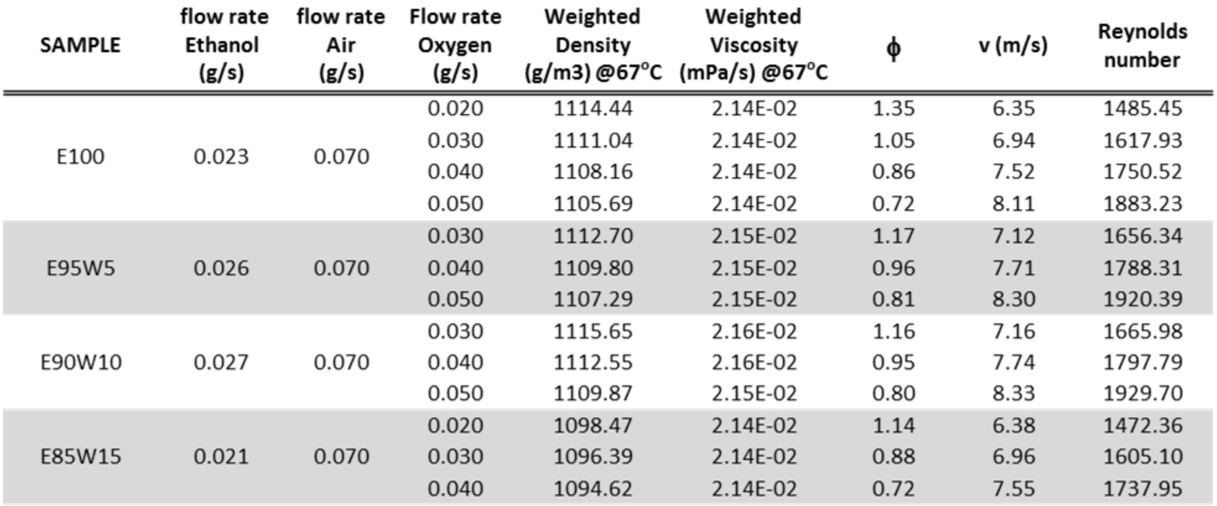
Ethanol is vaporized and is maintained warmed until reaches the burner by an electrical resistance at 250°C, preventing condensation in the walls. All the samples (Ethanol/Air/O_2) inflows the burner trough 0.8 mm orifices, in tubes with an inclination of 52°, as can be observed in Figure 2, at right.

Air and Oxygen flows were controlled through a flow meter from Aalborg, model GFM 17. This devices are based on thermal anemometry methodology for mass measurement, the uncertainty for each flow meter is $+10^{-3}$ g/s.

During the experiments, the fuel and air mass flow rates were constant and oxygen flow rate was varied in order to achieve different equivalence ratios from rich to lean conditions. It is important to say that O_2 was applied also for flame stabilization, this is the reason for being chosen for obtain different equivalence ratios for each experiment case.

The conditions studied are presented in Table 1.

Table 1. Flow conditions for the samples



SAMPLE	flow rate Ethanol (g/s)	flow rate Air (g/s)	Flow rate Oxygen (g/s)	Weighted Density (g/m3) @67°C	Weighted Viscosity (mPa/s) @67°C	ϕ	v (m/s)	Reynolds number
E100	0.023	0.070	0.020	1114.44	2.14E-02	1.35	6.35	1485.45
			0.030	1111.04	2.14E-02	1.05	6.94	1617.93
			0.040	1108.16	2.14E-02	0.86	7.52	1750.52
			0.050	1105.69	2.14E-02	0.72	8.11	1883.23
E95W5	0.026	0.070	0.030	1112.70	2.15E-02	1.17	7.12	1656.34
			0.040	1109.80	2.15E-02	0.96	7.71	1788.31
			0.050	1107.29	2.15E-02	0.81	8.30	1920.39
E90W10	0.027	0.070	0.030	1115.65	2.16E-02	1.16	7.16	1665.98
			0.040	1112.55	2.16E-02	0.95	7.74	1797.79
			0.050	1109.87	2.15E-02	0.80	8.33	1929.70
E85W15	0.021	0.070	0.020	1098.47	2.14E-02	1.14	6.38	1472.36
			0.030	1096.39	2.14E-02	0.88	6.96	1605.10
			0.040	1094.62	2.14E-02	0.72	7.55	1737.95

For each sample was calculated its respective stoichiometric fuel/air ratio, such way that the equivalence ratios for each sample could be obtained based on mass flow for premixed mixture (fuel, air and oxygen), within burner.

Total flow rate is controlled ensuring the laminar condition, in other words, Reynolds number <2000, (Fu et al (2013) and Dong et al (2009)). The conditions studied are presented in Table 1.

4.2 OH-PLIF

For OH-PLIF experiments, La Vision Flame Master System was applied. It consists of a 10 Hz pulsed Nd:YAG laser (Quantel, brilliant b model) at third harmonic beam producing a 366 nm output, it was used and laser energy of 1,2mJ/pulse . Dye laser consists of a Cobra Stretch Series – CSTR-G-3000, with Rhodamine 6G in ethanol solution. A LaVision ICCD camera, with a Nikon lens f/2 of 50mm with a resolution of 1376x1040 pixels was used for image caption. Its exposition time consists of an interval equivalent to 100 ns and a delay of 650ns, the gain applied was 90%.

During the experiments, OH in flames were excited in electronic transition $A^2\ \Sigma$ <- $X^2\ \Pi$ (1-0), corresponding to rotational line P1(9) in 286,203nm. For controlling of experiment and post processing of images was applied software DaVis 8.1.1. An ensemble average of 500 images was used for each specified case with all images being corrected and adjusted for intensity trough the energy monitor. Finally, the average image obtained was used as input for conical flame methodology application.

4.3 OH- Emission Spectroscopy

Emission spectroscopy is a non intrusive technique widely used for flame research. Its principle is based on species chemiluminescence and one of its advantages is the relative simple experimental set up required for the application.

Flame chemiluminescence is intrinsically related to the chemical kinetic of burning process. The resultant electronic excited radicals or molecules after achieve a high energy state tends to decay for a fundamental condition emitting light.

The experimental arrangement for Emission acquisition is similar to PLIF, except that laser is not applied this time, instead the capturing of spontaneous OH is captured by an OH filter assembled in ICCD. The exposition time has an exposition interval equivalent to 1 ms and the gain applied varies from 75% to 80%.

5. METHODOLOGY

5.1 Numerical Simulation: CHEMKIN

Aforementioned experimental cases on Table 2 were numerically simulated trough PREMIX code of CHEMKIN-PRO (Reaction Design, 2013) software package, predicting laminar flame speed as well as radicals distribution along flame path. Therefore, the results obtained from tests can be better understood and correlated to chemical mechanisms.

The reactor model considered is a premixed laminar flame stabilized flame. PREMIX code solves the set of governing differential equations that describes the flame dynamics using implicit finite difference methods, and a combination of time-dependent and steady-state methods. For temperature profiles prediction, the heat losses were not considered, despite the fact that for some cases this heat loss can be significant. Moreover, PREMIX accounts for finite rate chemical kinetics and mixture averaged or multi component molecular transport. For a system of algebraic equations, damped modified Newton algorithm is applied, and in case of divergence, the solution is conditioned by integration in time. The ordinary differential equations solution uses the backward-Euler method (Marques et al, 2010).

For all the investigated cases, the first-order sensitivity coefficients for OH and C_2H_5OH were calculated. The obtained matrix contains the sensitivity coefficients regarding the temperature and flame distance profiles. As they are in a quantitative format, it is possible to evaluate sets of mechanism reactions, and their respectively contribution to a chosen specie production, for example OH or its consumption or production effects an overall flame evolution.

Several researchers have studied and developed chemical kinetic mechanisms for ethanol flames, for example: Li et al. (2007), Saxena and Williams (2007), Konnov et al. (2009), and Marinov (1999), which is applied in the current study. Vancoillie et al (2012) have studied and compared all the mechanisms cited previously in different conditions to stablish the differences between the results obtained when applying different approaches in CHEM1D, the software used in their research. They have proposed a new modeling based on their results for a wide range of pressures, temperatures and equivalence ratios, once whenever working in engine-like conditions the different mechanisms cited did not present good correlations.

As long as this paper studies the flames in a fixed pressure and temperature conditions, Marinov´s mechanisms is a reliable choice. However, it is important to comment that the mechanisms available nowadays were developed considering pure ethanol. Therefore, the results obtained for simulations when those mechanisms are applied for hydrous ethanol should be analyzed carefully, because the influence of water in some reactions were not taken straightly into account.

5.2 Flame Speed measurement

The measurements of laminar flame speed were performed applying the flame cone area method based on the OH-PLIF images. The geometric parameters for the flame are directly obtained from OH-PLIF images trough DaVis software. The determination of flame surface for area estimative is an important factor for the laminar flame speed calculation, being one of the most contribution to uncertainties in this method. An example of how these values are obtained is shown on Figure 4.

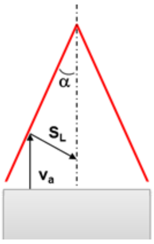


Figure 4. Scheme for conical flame methodology applied

Many optical methods can be used to determine the flame contour for the calculations, such as shadowgraph, Schlieren, PLIF, emission. For the last two techniques it is common to considerer the chemiluminescence for hydroxyl (OH), as long as it results in better correlations when comparing simulation versus experimental tests (Broustail et al, 2011, Dong et al, 2009).

The velocity of the unburned mixture (Equation 2) at the nozzle exit of Bunsen burner can be assumed as constant and uniform, and the total mass balance is used in order to calculate the average flame speed. So the laminar flame speed can be expressed by Equation 2.

$$S_L = \frac{\dot{Q}}{A} = \frac{\dot{m}}{\rho \times A} \tag{2}$$

Where, $Q^{\cdot}$ is the volumetric flow rate, $\dot{m}$ is the total flow rate, ρ is the weighted density for each mixture and A is the surface flame area.

6. RESULTS

6.1 Fuel Characterization Analysis

The properties for the fuel samples used in this study are presented in Table 2.

Table 2. Fuel samples analyzed.

SAMPLE	DENSITY (g/cm3)	% Alcoholic Content vol. (OIML)	% Alcoholic content weigth (OIML)	HIGH HEAT VALUE (kJ/kg)	LOW HEAT VALUE (kJ/kg)
E100	0.7915	99.557	99.270	29176.5	26501.5
E95W5	0.8040	96.823	95.037	28048.0	25210.9
E90W10	0.8164	93.670	90.553	26758.0	23871.2
E85W15	0.8307	89.540	85.070	25201.0	22121.4

* High and low heat values evaluated according to ASTM D240-14

6.2 Laser Images analysis

Data obtained for laminar flame speed for the test conditions described previously are presented in this section.

Figure 5 presents the results obtained for LFS based on OH-PLIF measurements and on OH-chemiluminescence. The calculation for conical flame is based on methodology described on Figure 4 and in Equantion 2.

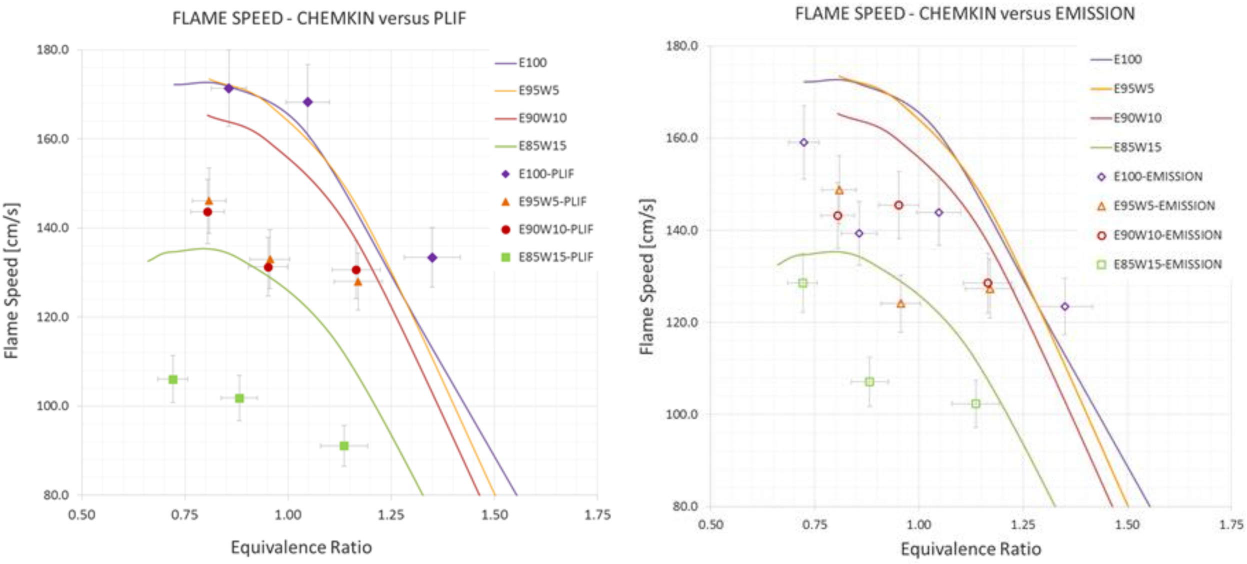


Figure 5. Curves obtained on CHEMKIN simulation and experimental data for different equivalence ratios considering E100, E95W5, E90W10 and E85W15. At left with OH-PLIF and at right with OH-chemiluminescence.

As can be observed, they presented good correlations with CHEMKIN, mainly for E100 and E95, although for mixtures with higher water content (E90W10 and E85W15), the simulation indicated that for the majority of the cases higher values for flame speed than the ones obtained through PLIF experiments acquisition.

The uncertainties obtained for PLIF experiments are at most equivalent do 5.5%, for the leanest conditions, and around 2% for richer conditions. Besides the equivalence ratio uncertainties varies from 19% to 5%, for richer to leaner cases, respectively.

Another source of experimental uncertainty is associated to the heat exchange between burner and flame, which is associated to uncontrolled upstream burner temperature. This point was not considered in the present study. As cited by Fu et al (2013), the systematic error intrinsic to temperature variation on burner could lead to under estimated LFS, due to the lower flame area estimative by image measurement and propagated to flame surface area calculation.

Figure 6 shows a set of images obtained for all equivalence ratio conditions tested in PLIF experiment for E100, E95W5, E90W10 and E85W15, respectively.

Figure 7 shows a set of images obtained for the Emission experiment for E100, E95W5, E90W10 and E85W15.

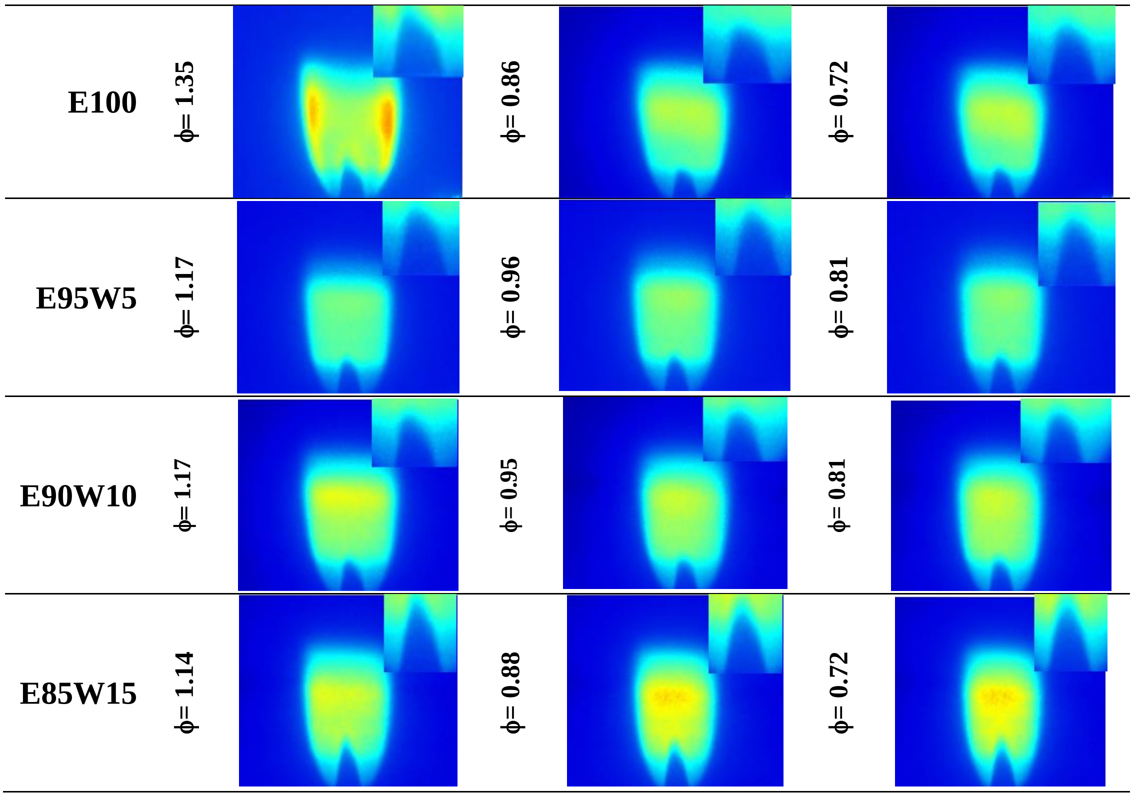


Figure 6. Images obtained for OH- PLIF acquisition, considering four fuel blends.

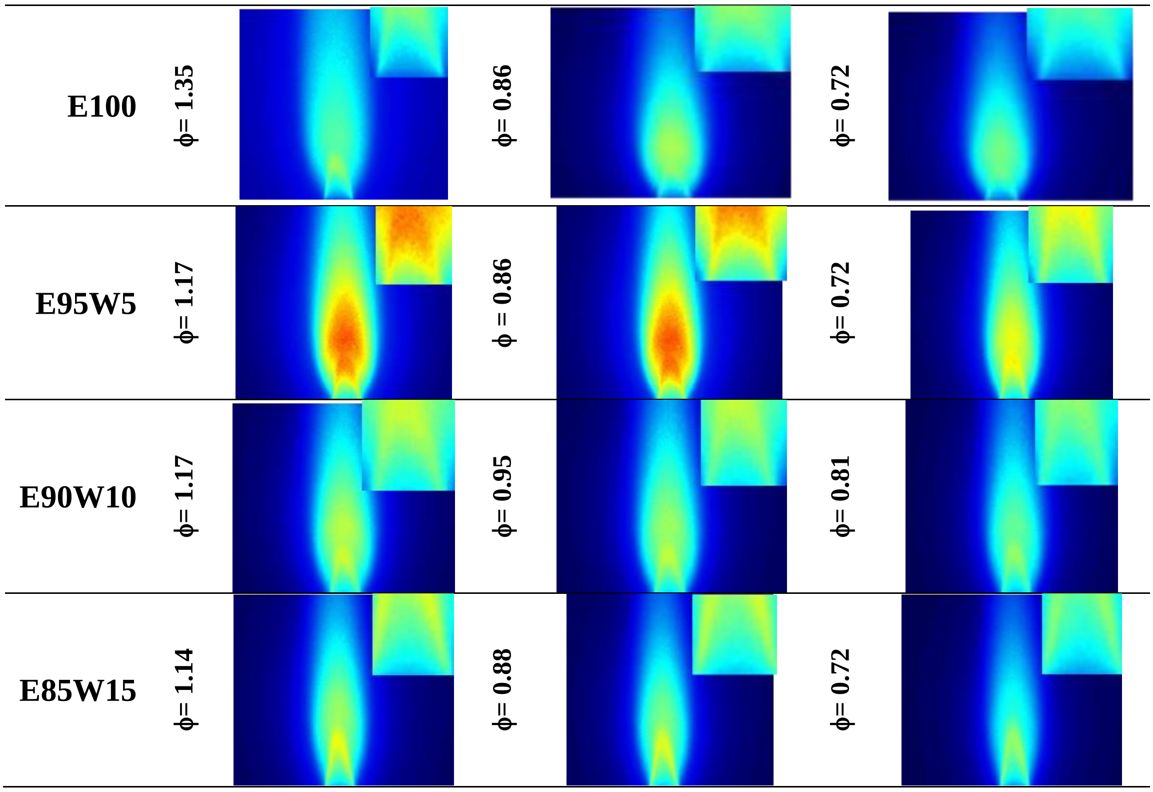


Figure 7. Images obtained for Emission acquisition, considering four fuel blends.

For all the cases, the reaction zone is well defined for the excited OH. Besides, it can be observed that OH distribution shifts away from reaction zone, presenting high concentration above flame tip for all the cases. Therefore, as water content increases in fuel sample, the OH distribution tends to be closer to flame base and along reaction cone. This behavior could indicate a lower diffusivity in the mixture due to water presence in ethanol sample.

The profile for reaction zone in a region close to the tip and even for OH caption is slightly distorted to left side, probably due to a deficiency of the apparatus to keep the mixture flow unidirectional as it leaves the burner orifice.

Regarding the uncertainties obtained in the tests, it can be observed in Figure 5 that, for Emission experiments they are at most equivalent do 6.5%, for the leanest conditions, and around 3% for richer conditions, in other words 1% higher than PLIF results. The equivalence ratio uncertainties varies from 19% to 5%, for richer to leaner cases, respectively. All the error bars are presented in the plots for the respective experimental set ups.

For emission experiments the influence of heat losses were not considered, same as for OH-PLIF acquisition. Therefore, it could lead to under predicted values for LFS. Another source of error in this part of experiment is the high amount of OH presented at the superior part of flame, impairing accuracy for flame tip determination.

The reaction zone is well defined for the OH radical for side limits of the flame, but in superior portion of flame, it is difficult to define the end of the reaction zone at the flame tip, due to high concentration of OH radical in a post flame region.

Correlating these images to those presented for OH-PLIF acquisition, the hypothesis of a continuity of reactions, which produce OH after the reaction zone regions can be confirmed. The high OH concentration was observed for all the four fuel samples analyzed in this study.

Figure 8 presents the analysis for sensitivity coefficients obtained for Ethanol considering the four fuel samples analyzed. Highest sensitivity coefficients for reaction HCO+M=H+CO+M, are observed for rich regimes, increasing proportionally as water content increases in fuel samples, and with decrease in oxygen supply for pre mixture preparation. Moreover, the most affected reaction by O_2 content on mixture preparation is $H+OH+M=H_2O+M$, and the highest rates can be observed in anhydrous and on E85W15 samples. As both reactions are third body reactions it can be inferred that, the addition of O_2 in the mixtures has changed the path mechanisms for this reactions, affecting also OH rates of consumption.

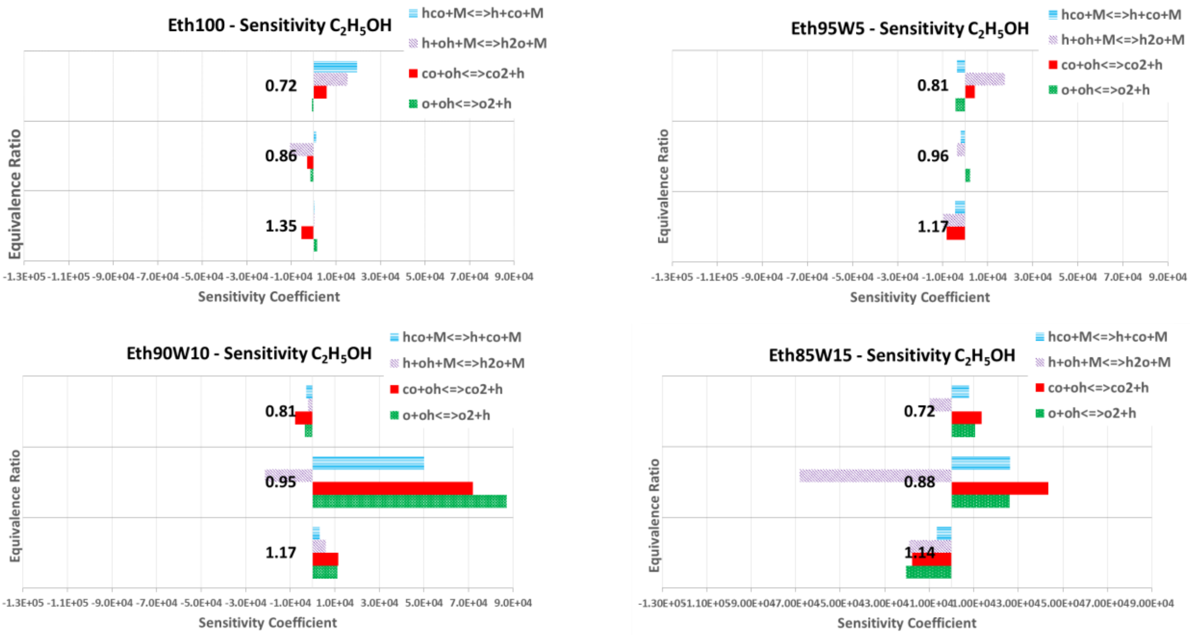


Figure 8. Sensitivity Coefficients for Ethanol (C_2H_5OH), considering four fuel samples.

Figure 9 presents the sensitivity analysis coefficients obtained for Oxygen considering the four fuel samples analyzed.

Analyzing the images from Figure 6, it can be seen that the richest conditions for all four fuel samples present most OH* intensities, except by E100 and E85W15, which intensities on richer flames are not so evident. In parallel, when analyzing the plots for O_2 sensitivity on Figure 9, the third body reaction related to OH consumption presented highest sensitivities for both fuels as well. This changing in reaction rate can be related to the addition of O_2 in the premixed mixture, affecting in a most evident manner only these samples (Chin et al, 2008; Higgins et al, 2001).

In other hand, reaction $CO+OH=CO_2+H$ does not present differences on sensibility coefficients neither when water content on fuel samples are considered nor when combustion regime is modified regarding rich or lean conditions. Reaction $O+OH=O_2+H$ presents sensibility for anhydrous and for ethanol blend with highest water content, in both cases on rich conditions (EQR>1).

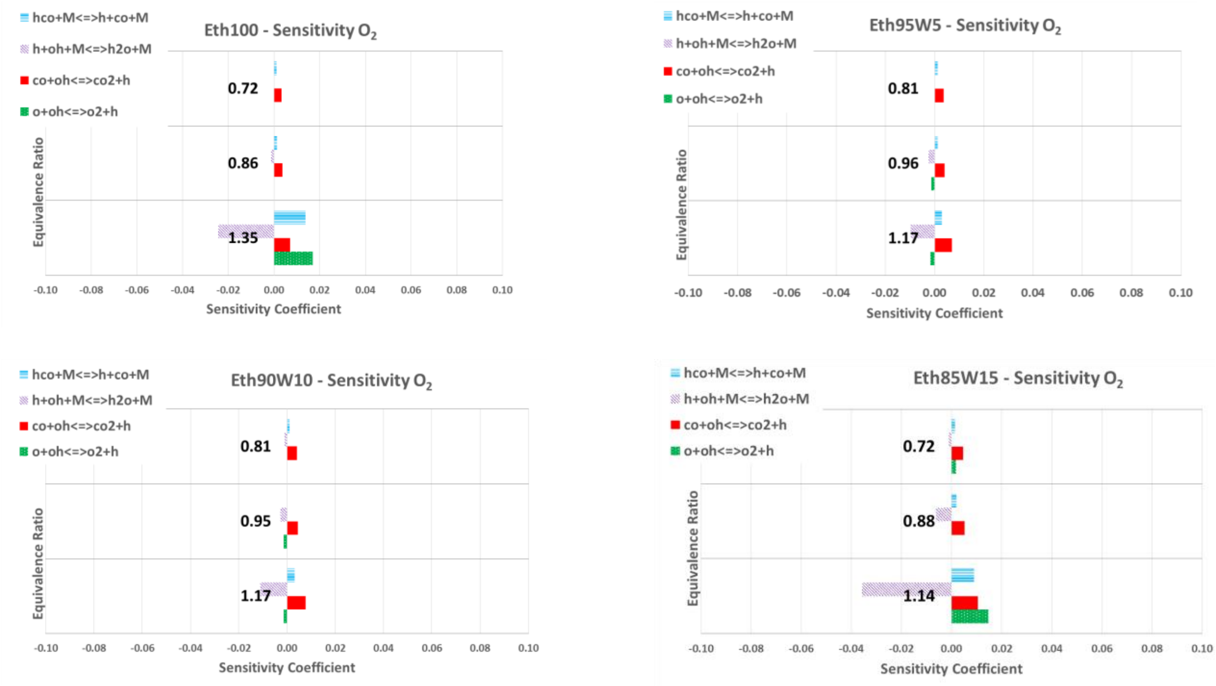


Figure 9. Sensitivity Coefficients for Oxygen (O_2), considering four fuel samples.

7. CONCLUSIONS

The current research work studied the laminar flame speed in a Bunsen burner for anhydrous ethanol, and three hydrous ethanol samples (E95W5, E90W10 and E85W15). Fuel characterization was performed in order to evaluate the samples to be tested. Then, OH-PLIF and OH-Emission was used in order to obtain images from reaction zone and flame cone methodology was applied for laminar flame speed determination. Chemical kinetic simulation on CHEMKIN-PRO was used to correlate experimental versus simulated data.

Generally, OH-PLIF images presented a better accuracy on zone reaction determination when compared to OH-Emission. Consequently, the laminar flame speeds calculated when these images are used are sensibly closer to values obtained through simulation. Therefore, it is observed a high amount of OH on Emission acquisition, which jeopardized the determination of reaction zone tip, and consequently, the determination of flame surface area.

The images obtained for OH-PLIF and for OH-Emission present completely distinct shapes, what could be explained by the increase observed in Oxygen sensitivity coefficients on Figure 9. As richness of pre-mixtures increases, the O_2 sensitivity rises proportionally, changing the OH production reactions behavior. Moreover, when correlating the images to Figure 6, it can be inferred that the high amount of OH presented on laser images are related to the increasing of rates of production and consumption of OH radical in the plots. The plots for the chosen set of reactions show an intrinsic relation between the water content in fuel samples and in Oxygen addition in the pre-mixtures.

Many factors were pointed during analysis of results regarding items to be taken into account, such as the control of burner temperature, avoiding heat exchange between flame and burner, diminishing experimental uncertainty. Another observation for future work would be add a diffuser before burner outlet assuring the unidirectional flow for the upstream pre-mixture flow, avoiding distorted reaction zone formation.

As a final remark a second experiment could include a distinct geometry for Bunsen burner, in such way that zone reaction stability could be guaranteed without the O_2 addition. The application of a coaxial jet in the burner could help to stabilize the flame and turn possible to study distinct flame burning regimes (laminar or turbulent) trough different flow velocities (Kiefer et al, 2008).)

Summarizing, based on the experiments conducted in this analysis it can be concluded that the laminar flame speed is quite affected by water content in the fuel sample, diminishing with H_2O addition. Besides, the differences presented on excited and spontaneous OH production indicates that further investigation is needed relating the effects of Oxygen to flame behavior and reaction mechanisms.

8. ACKNOWLEDGEMENTS

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