Laminar Burning Velocity and Markstein Length Relative to Fresh Gases Determination for Isooctane-Ethanol Air Flames

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1 Introduction

Massive consumption of fossil energy leads to higher and higher pollutant and greenhouse gas emissions. Both ecological and political contexts encourage scientists and engineers to find new bio solutions for sustainable development. Transport is one of the first challenges because of its quasy-total dependence on fuel. Automotive industry is working at the same time for increasing engine efficiency but mainly on bio blended fuel combustion and characterization. Unstretched laminar burning velocity u_n^0 is an essential value for fuel description (reactivity, ignition delay times, energy released) and it is necessary for kinetics mechanisms validation and tabulated chemistry. It is also useful for turbulent combustion modeling. In this study, ethanol has been chosen as bio fuel. Previous works of Egolfopoulos [1] had characterized ethanol combustion over ranges of equivalence ratios and temperature (363-443K) with counter-flow flame at atmospheric pressure. Recently, Bradley [3] proposes characterization of pure ethanol air flame up to 1.4MPa in a spherical bomb. Even if those studies describes for ranges of equivalence ratios and temperatures ethanol combustion, very few studies exist for blended isooctane-ethanol fuels and also for thermodynamic conditions close to those encountered in internal combustion engine: 2MPa, 573K. Spherical combustion is a well-known technique for burning velocity u_n^0 measurement. It consists in determining the evolution of flame speed, S_f , derived from radius information (dr/dt) in respect with stretch factor $\alpha = 2/rS_f$. Stretch factor takes into account strain effects and curvature. Extrapolation at zero stretch of flame speed, S_f^0, that gives the corresponding velocity of a propagative plane flame is corrected by the density ratio at the interface Eq.1.

$$u^0_{nS_f} = \rho_b/\rho_u S_f^0 \tag{1}$$

It allows considering the thermal expansion part in flame propagation. Extrapolation at zero stretch is a critical point. Asymptotic developments demonstrates that flame speed to stretch factor are nonlinearly linked [8], Eq.2:

$$\left(\frac{S_f}{S_f^0}\right)^2 ln\left(\frac{S_f}{S_f^0}\right)^2 = -2\frac{L_b\alpha}{S_f^0} \tag{2}$$

where L_b is the Markstein Length relative to burned gases. It can be easily shown that when S_f/S_f^0 is close to unity, linear formulation is recognized : $S_f = S_f^0 - L_b\alpha$. Recent works had investigated the importance of nonlinear effects of stretch on spherical expanding flames as [10,13]. Fig.1 shows the differences of laminar burning velocity obtained with linear or nonlinear extrapolation on pure ethanol air flame.

It is important to note that linear extrapolation mainly used in literature overestimates burning velocity when non-unity S_f/S_f^0 hypothesis is not validated. This technique has demonstrated its efficiency for well-known mixtures but shows its limitation when exotics blends are studied. The main disadvantage of the common method is that fuel properties are absolutely necessary (ρ_b/ρ_u) and are usually determined thanks to kinetics mechanisms and thermodynamic tables under adiabatic conditions. Also, only zero stretched laminar flame speed and Markstein length relative to burned gases (L_b) can be extracted. Due to its specific hypothesis, it does not allow considering the evolution of burning rate as a function of stretch. This study proposes an approach for laminar burning velocity and fresh gases Markstein length (L_u) determination applied on spherical expanding flame.

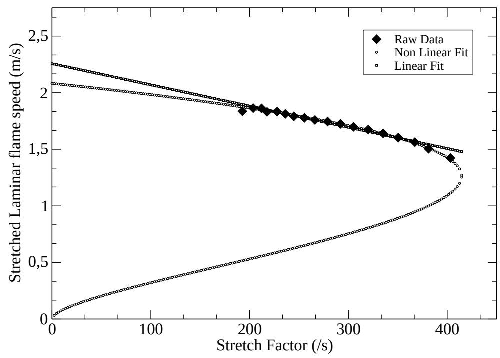


Figure 1: Linear and nonlinear extrapolation of unstretched laminar flame speed S_f^0 determination. (Ethanol-Air Flame ϕ=0.7, P=0.1MPa, T=373K)

2 Methodology

The technique proposed in this study consists in a pure kinematic measurement. The decomposition formulation leads to the direct expression Eq.3 [2,12]:

$$u_n = S_f - u_g \tag{3}$$

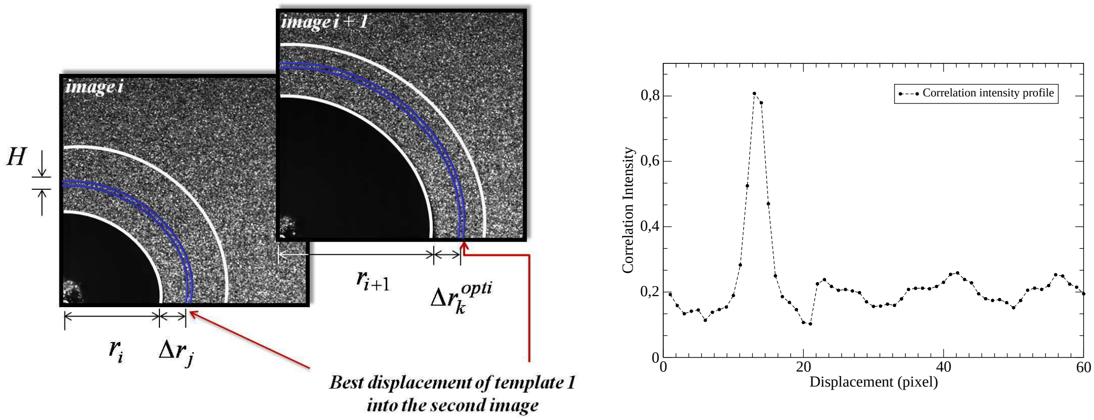
where u_g describes the fresh gases velocity ahead of the flame front. This calculation is arduous because fresh gases velocity needs to be calculated at the entering of the preheat zone [9]. That corresponds to a distance smaller than 1mm from the flame front ($\leq 20pixels$). It is worth noting that this approach does not introduce any chemical fuel properties. The recent work of Balusamy et al. [7] demonstrates the interest of this approach. This paper proposes to extend this work for direct measurements of laminar and unstretched laminar burning velocity by fresh gases velocity determination by using high speed laser tomography. This technique is based on a two-step calculation method.

First, an accurate flame front determination is required. A specific algorithm with adaptive threshold can determine locally the optimized threshold value. The extracted raw contour is then low pass filtered reducing noise from digitization. For each images, a least square algorithm calculates the best circle fit to the raw contour and then the corresponding radius. An accurate contour determination is essential for the second step.

Second, for an images couple, a variable 3-4 pixels width thin corona, blue marked in Fig.2(a), is fixed at a specific position Δr_j from the filtered contour on the first image. The best displacement Δr_k^{opti} of this corona in the second image is then evaluated with a sub pixel interpolation of the correlation coefficient intensity in Fig.2(b). The fresh gases velocity along the normal to the flame front, u_g*, is given by this expression Eq.3:

$$u_g* = \frac{r_{i+1} - r_i}{\Delta t} + \frac{\Delta r_k^{opti} - \Delta r_j}{\Delta t} \tag{4}$$

It can be describes as a specific movement of particles transported at the flame speed $S_f = \frac{r_{i+1}-r_i}{\Delta t}$. The fresh gases profile of u_g*, ahead of the flame front, can be reconstructed iterating this previous calculation for increasing j shift positions (Δr_j) as shown in Fig.3. The fresh gases velocity, u_g, used in Eq.3 corresponds to the value at the entering of the preheat zone. It is given at the plato of the profile in Fig.3 as explain in [7, 9]. Finally, flame speed evolution, function of stretch factor, is corrected, subtracting the corresponding fresh gases velocity u_g.



(a) Calculation scheme showing the flame front displacement and the particles displacement (b) Position of the maximum correlation intensity profile

Figure 2: Calculation scheme and correlation intensity profile

A nonlinear extrapolation at zero stretch is calculated minimizing the analytical expression Eq.5:

$$\left(\frac{u_n}{u_n^0}\right)^2 ln\left(\frac{u_n}{u_n^0}\right)^2 = -2\frac{L_u\alpha}{u_n^0} \tag{5}$$

explained in [8], where L_u is the Markstein length relative to the unburned gases (i.e. fresh gases).
As presented in [2] both methodologies, $u^0_{nS_f}$ and u^0_n from Eq.1 and Eq.3 gives the same zero stretch value if the simplification hypothesis (adiabatic flame temperature, perfect gases, isobaric conditions) in the classical method (Eq.1) are verified. In Fig.4, raw data for S_f, u_g and $Eq.3$ with respective non linear fits are plot. It is also plot, and only for the form, $Eq.1_{modified}$:$u_{nSf} = \rho_b/\rho_u Sf$. It has absolutely no physical sense (it imposes a zero flame thickness [2]) but represents, for a zero stretched flame, the convergence of both methodologies mentioned above.
Validation of the post processing tool has been tested on well-known $CH_4 - Air$ mixtures for large ranges of equivalence ratios, pressures and temperatures [5]. Based on this validation, this paper presents results on pure ethanol air flames at 0.1MPa, 373K for corresponding range of equivalence ratios 0.7-1.5. Laminar burning velocities and fresh gases Markstein Length from the new calculation algorithm are compared to literature.

3 Experimental set-up

A 2.6 liters constant volume vessel has been designed with four 85mm optical access (Fig.5). Maximum pressure and temperature ranges are respectively 2MPa, 573K. The specific technique in this experiment consists in flow fed the chamber with the desired (pressure, temperature and equivalence ratio) mixture.

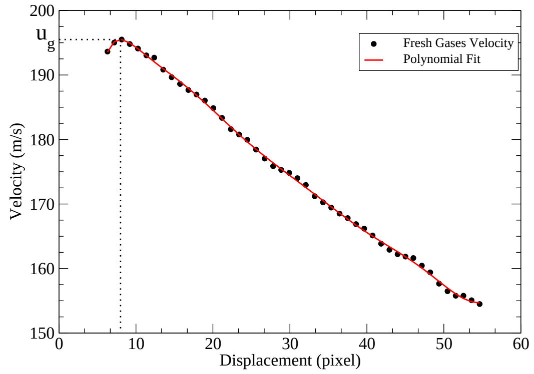


Figure 3: Fresh gases velocity profile and u_g localization

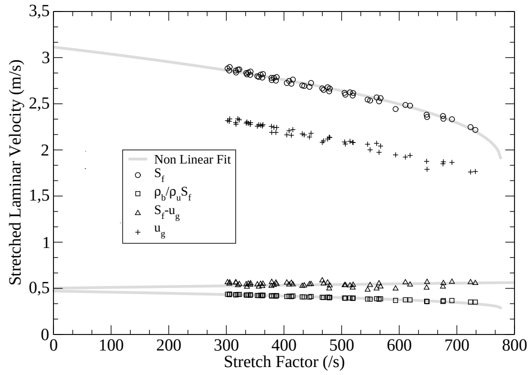


Figure 4: Velocity plots. From the top to the bottom: Flame speed: S_f, Fresh gases velocity: u_g, u_n from Eq.3 and u_{nSf} = $\rho_b/\rho_u S_f$ from $Eq.1_{modified}$ (Ethanol-Air Flame ϕ=1, P=0.1MPa, T=373K)

All the individual flows are controlled thanks to mass flow controllers and liquid fuels are vaporized and blended with the other gases before entering the chamber. The main advantage of this experiment is that low time residence in the chamber reduces fuel degradation. When a constant flow regulation is reached, the chamber is isolated and the mixture is spark ignited thanks to two 0.5mm diameter electrodes. Electrodes gap is kept constant (1.5mm) and energy can be adjusted in order to ignite with the minimum necessary.

The flow is also seeded with silicon oil (vaporization @ 580K) allowing optical diagnostic such as high speed tomography. Seeded flow is illuminated with a double cavity Nd:YLF laser, 2*28mJ, (Darwin Dual). Mie scattering of particles is recorded thanks to an high speed Photron camera at 5kHz mounted with a Nikon 105mm focal length. The 1024pixel^2 images returns a 50mm^2 field of view allowing a 0.049 mm/pixel resolution. Validation of the facility under high pressure and temperature are presented in [5].

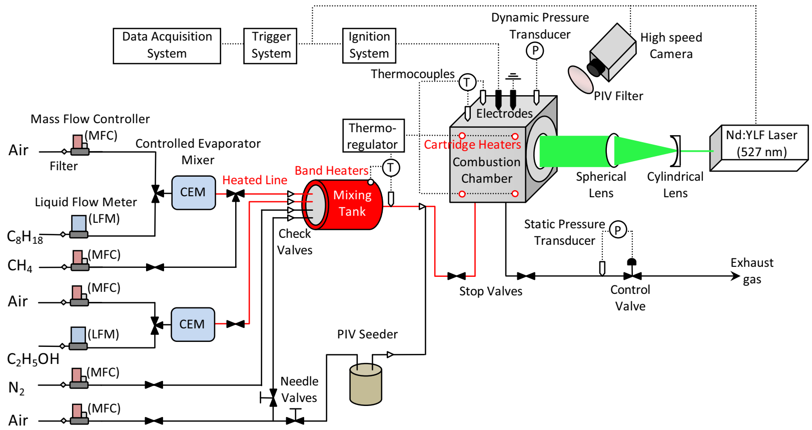


Figure 5: Experimental set-up scheme

4 Validation, results and discussion

As mentioned above, nonlinear extrapolation seems to be more accurate and the results presented in this study are extracted from nonlinear form. In literature, for ethanol air mixture, mostly linear extrapolation to zero stretch are present $[1, 3, 6]$ excepted those recent in [11]. In Fig.6 laminar burning velocities from literature as a function of equivalence ratio and those obtain in present work are presented for pure ethanol. It is important to note that differences on laminar burning velocity values can be linked to the effect of temperature (358-393K). It also shows that results are consistent with literature values. The two techniques Eq.3 and Eq.1 present the same trend with equivalence ratio, but some differences exist between both techniques: results from Eq.1 are smaller than those obtained with Eq.3. Those differences could be due to the estimation of the burned gases density ρ_b by using adiabatic flame temperature.
The consistent of the new methodology also allows to reduce the influences of ignition energy necessary to ignite the combustion process. As shown in Fig.7, two different values of initial energy, called *sup* and *inf*, leads to two different flame speed and fresh gases velocity behaviors. Then, the unstretched laminar flame speeds extracted with non linear extrapolation are different, 3.4 and 3.7m/s (9% error) respectively. Consequently, the two unstretched laminar burning velocities calculated thanks to Eq.1 are different. On the other side, the methodology (Eq.3), is much less sensitive to the influence of ignition energy. In Fig.7 it can be shown that thanks to the new method, that extrapolation at zero stretch of stretched laminar burning velocity is equal in the two cases because fresh gases velocity follow the flame speed evolution.
Markstein lengths L_b that gives flame sensitivity to stretch factor can be also estimated. They are extracted from linear and nonlinear relations respectively:
$S_f = S_f^0 - L_b\alpha$ and from Eq.2. From Eq.5, the chemical burning rate dependence to stretch L_u is also estimated. Markstein lengths: $L_{b,lin}$ and $L_{b,nonlin}$ and are reported on Fig.8 for both cases. The present values of L_b are compared with [3] and are in very good agreement for linear cases.
Markstein lengths relative to fresh gases are presented in Table:1. It can be seen that a change of slope appears at an equivalence ratio between 0.8 and 0.9. It means that, as shown in Fig.9, the dependence of laminar burning velocity to stretch factor is inverted for this specific equivalence ratio ϕ_{invert}.

ϕ	L_u	ϕ	L_u	ϕ	L_u
0.7	0.07	1	-0.153	1.3	-0.221
0.8	0.062	1.1	-0.155	1.4	-0.242
0.9	-0.036	1.2	-0.183	1.5	-0.261

Table 1: Markstein Length L_u (mm) as a funstion of ϕ

5 Conclusion

This paper had proposed an experimental approach for laminar burning velocity measurements for spherical expanding flames. It consists in determining on tomographical images the information corresponding to fresh gases velocity ahead of the flame front. It has shown its efficiency on a pure ethanol air flame for a range of equivalence ratios from 0.7 to 1.5. This new approach also gives an essential key parameter on flame combustion behavior to stretch factor that is Markstein length relative to fresh gases L_u. New set of measurements are in progress for ranges of temperature and pressure up to 573K, 2MPa. Characterization of pure ethanol and blended isooctane-ethanol burning velocity on thermodynamics conditions above mentioned will be exposed on further works.

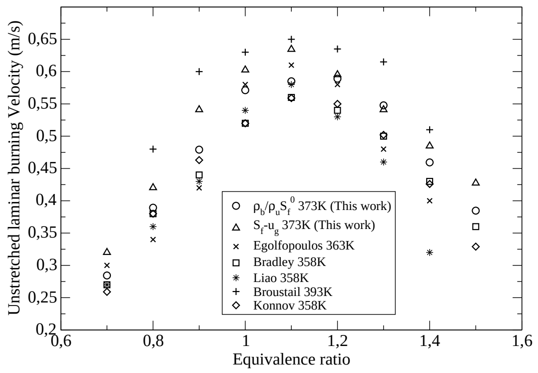


Figure 6: Present values of laminar burning velocities compared with those from literature [1, 3, 6, 11, 14] at given temperatures. (Ethanol-Air Flame P=0.1MPa)

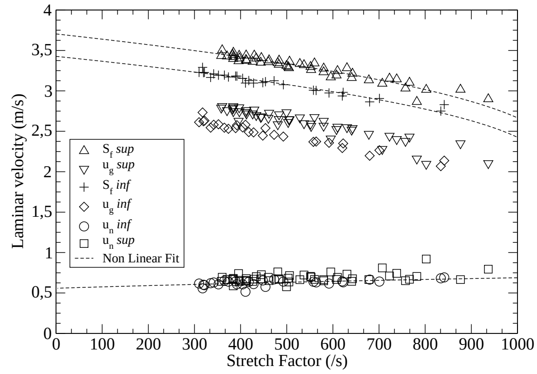


Figure 7: Evolution of laminar flame speed, fresh gases velocity and resultant laminar burning velocity for two different initial ignition energies called *sup* and *inf* (Ethanol-Air Flame P=0.1MPa, T=373K)

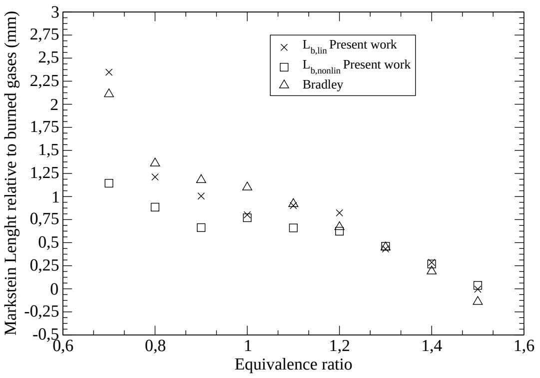


Figure 8: Markstein length relative to burned gases $L_{b,lin}$ and $L_{b,nonlin}$ compared to [3] (Ethanol-Air Flame P=0.1MPa, T=373K)

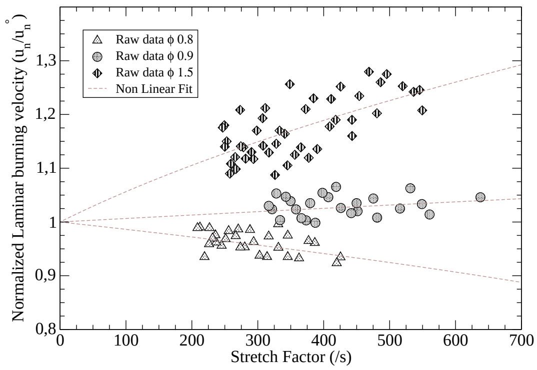


Figure 9: Normalized laminar burning velocities for mentioned ϕ : 0.8, 0.9, 1.5 (Ethanol-Air Flame P=0.1MPa, T=373K)

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