Determination of α-Pinene/Air Premixed Flame Speeds Involved in Accelerating Forest Fires and Real Accidents

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1 Introduction

Forest fires are responsible for important damages every year, in economical and ecological terms as well as in human lives losses. They can cause important disturbance to ecosystems and, due to global warming, they are becoming an increasing threat for countries at the North of the Mediterranean Sea but also for other regions in the world. The average surfaces destroyed by forest fires every year all over the world and in Europe are respectively 28 and 1.6 billion ha.

Several researches ([1], [2], [3]) have reported that under certain conditions wildland fires behave in a surprising way, changing suddenly from an ordinary behavior (moderate rate of spread) to an explosive propagation (rate of spread and energy released much more important). This phenomenon is called forest fire blowup or accelerating forest fire for its explosive nature, or eruptive fire for its rate of spread continuous increase. Fires propagating in canyons can lead to such fire explosions and are responsible for many fatalities in the past. Indeed, the Guadalajara accident in Spain in 2005 caused the death of eleven persons ([4]). More recently, this phenomenon happened in Artemida (Greece, 2007), killing 24 persons ([5]).

The mechanisms which explain this type of forest fires are not totally well known yet. There are nowadays two hydrodynamic approaches to explain this phenomenon. The first one is based on the feedback effect of the convection induced by the fire which can happen naturally in steep terrains ([6]). The second explanation is that this phenomenon is the result of an increase of the rate of spread caused by flow attachment in the direction of the fire spread ([7]). A thermochemical approach, based on the ignition of a Volatile Organic Compounds (VOCs) cloud, has been proposed in [8]. According to these authors, the acceleration of the rate of spread is the consequence of the ignition of the VOCs emitted by fire heated vegetation and accumulated in canyons. They have shown that monoterpen hydrocarbon ($C_{10}H_{16}$) α-pinene is the major component emitted by a *Rosmarinus Officinalis* plant when heated by a radiant panel simulating the fire front. The molar composition of the mixture α-pinene and sum of the other compounds emitted at different temperatures is presented in Table 1.

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Table 1. Molar percentages of α-pinene in the VOCs mixture emited by *Rosmarinus Officinalis* at different temperatures.

Temperature (°C)	36	39	55	80	115	138	151	171	175	177	202
α-Pinene (% mol.)	75.4	47.3	72.8	56.7	48.6	76.9	78.1	56.8	15.7	71.6	74.3
Others (% mol.)	24.6	52.7	27.2	43.3	51.4	23.1	21.9	43.2	84.3	28.4	25.7

Very recently, it has been demonstrated using empirical correlations in [9] that the VOCs mixture is in the flammability domain in canyons where real accidents occurred. Forest fires propagation models do not take yet into account this possible VOCs cloud ignition. A good modeling of such a phenomenon requires measurements of the laminar burning speed of these VOCs. Knowing this fundamental parameter, it will be possible to predict these accidents with the existing propagation models ([10], [11]). The spherical expanding flame method ([12], [13]) has been chosen to determine the laminar combustion fundamental parameters of α-pinene. This is the aim of this study. The experimental setup and conditions are presented, followed by the methodology used to determine the stretch influence on the flame speed. The flame speeds of α-pinene/air mixtures as functions of equivalence ratio for different temperatures are then presented, discussed and compared to those obtained with real accidents.

2 Experimental setup and methodology

The laminar flame velocity measurements were made using a stainless steel spherical combustion chamber. Before filling the chamber, vacuum was first created. The amount of gases introduced into the chamber was controlled with a thermal mass flow meter. Synthetic air (79.5% N_2 and 20.5% O_2) was used for the experiments. High purity α-pinene ($\geq$ 98%) was injected through a Coriolis mass flow meter. The mixture was heated up to 180°C to allow liquids full vaporization and the chamber minimum temperature was fixed for these experiments at 80°C to avoid VOCs condensation on the sphere walls. The temperatures chosen to study the effect of temperature on the flame speed were: 80, 100, 125, 150 and 180°C. They are very close to the temperatures of Table 1. The range of equivalence ratio Φ was chosen between 0.7 and 1.4 with a 0.1 step. An electric fan, located inside the chamber, mixes all the gases. Two tungsten electrodes were used to produce spark ignition at the center of the chamber. For each condition, measurements were repeated three times.

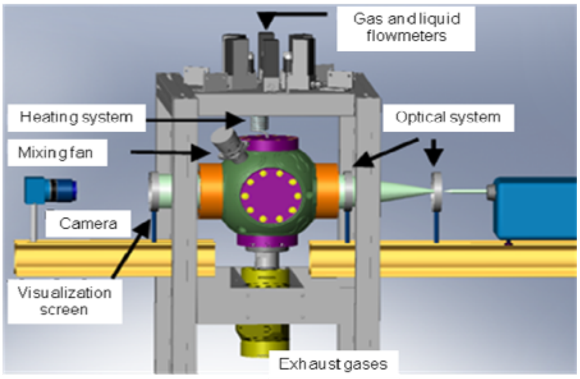


Figure 1. Scheme of the experimental setup.

The flame images were obtained by shadowgraphy. The temporal evolution of the expanding spherical flame was then analyzed. Fig. 1 presents a schematic overview of the system. During the initial stage of flame expansion, the total chamber pressure was constant, so flame radii larger than 25 mm were not taken into account, corresponding to a total volume of burned gases less than 1.6% of the chamber volume.

Flame stretch influences propagation, stability and structure of the premixed flames and affects their speed determination. Under the hypotheses of low stretch values and high activation energies, it has been shown that the stretched premixed flame speed was linked to the stretch by the following relation:

$$S_b = S_b^0 - L_b \kappa$$

where S_b is the stretched flame speed, S_b^0 is the unstretched one, L_b is the Markstein length and κ is the flame stretch. This linear extrapolation has been widely used in the literature ([12], [14], [15]) to determine spherical expanding unstretched flame speed. Indeed, in [12], the effects of hydrogen addition and nitrogen dilution on the laminar flame characteristics of premixed methane/air flames in ambient conditions have been studied. In [14], authors have determined the effect of pressure and temperature on the laminar flame speeds and Markstein lengths of iso-octane/air and iso-octane/n-heptane/air mixtures. In [15], they have determined Markstein length and laminar flame speed of methanol/air mixtures, taking into account pressure and temperature influence.

This relation is easy to use but a particular care must be provided to ensure the relevance of results. In some cases, the gap between stretched and unstretched flame speed values becomes important, due for example to high stretch values, and this linear interpolation becomes untrue ([16], [17]). This is the reason why a nonlinear formulation has been used to link the stretched flame speed, the unstretched one, the Markstein length and the stretch in order to determine the premixed flame characteristics of n-butane/air mixtures, [16]. In [17], the same formulation was obtained using a simplified model coming from a detailed one.

In this study, we are going to focus on the method proposed by [17]. The simplified model used here is given by the following expression:

$$\left(\overline{s}_b + \frac{2}{\overline{R}}\right)\ln\left(\overline{s}_b + \frac{2}{\overline{R}}\right) = \frac{Ze}{\overline{R}}\left(\frac{1}{Le} - 1\right) - \frac{2}{\overline{R}}\left(\frac{1}{Le} - 1\right)$$

where Ze and Le are respectively the Zeldovich and Lewis numbers and $\overline{s}_b$ the normalized unstretched flame speed.

The analytical solution of the flame radius can be given by the following expressions:

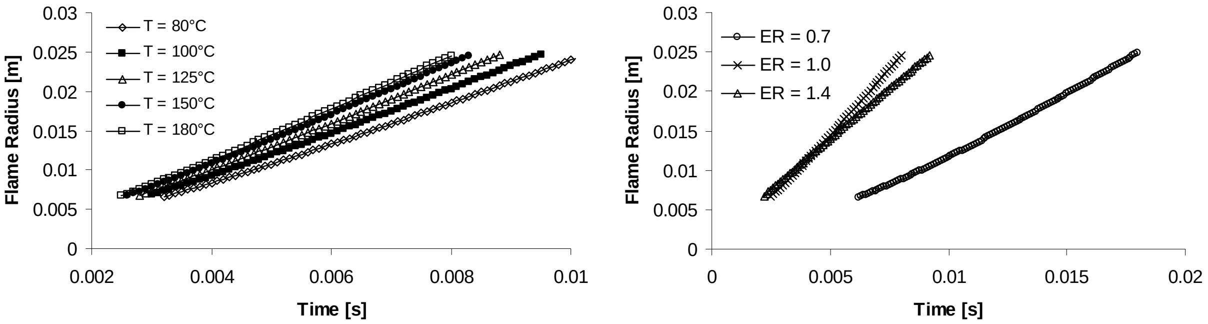
$$\begin{cases} t = \dfrac{2L_b}{s_b^0}\left[E_1\left(\ln\eta^2\right) - \dfrac{1}{\eta^2 \ln\eta}\right] + C \\ R_f = -\dfrac{2L_b}{\eta\ln\eta} \end{cases}$$

where $E_1(\eta) = \int_\eta^\infty \frac{e^{-x}}{x}dx$ is the exponential integral function and C a constant.

The unstretched flame speed S_b^0 and the Markstein length L_b can be determined using the temporal evolutions of the stretched flame speed obtained with experimental flame radii derivation and with the analytical solution of the previous expression. These two parameters are then obtained by minimization using the Simplex algorithm, which is a direct research method where no function gradient information is necessary.

3 Flame speeds

Temporal evolutions of the flame radius of α-pinene/air stoechiometric mixtures are presented in Fig. 2.a for different temperatures. In previous works, [8] and [9], we have shown that the maximum VOCs amount emitted by a heated *Rosmarinus Officinalis* shrub is around 180°C. At this temperature, Fig. 2.b illustrates equivalence ratio effect on the temporal evolutions of the flame radius for these mixtures.

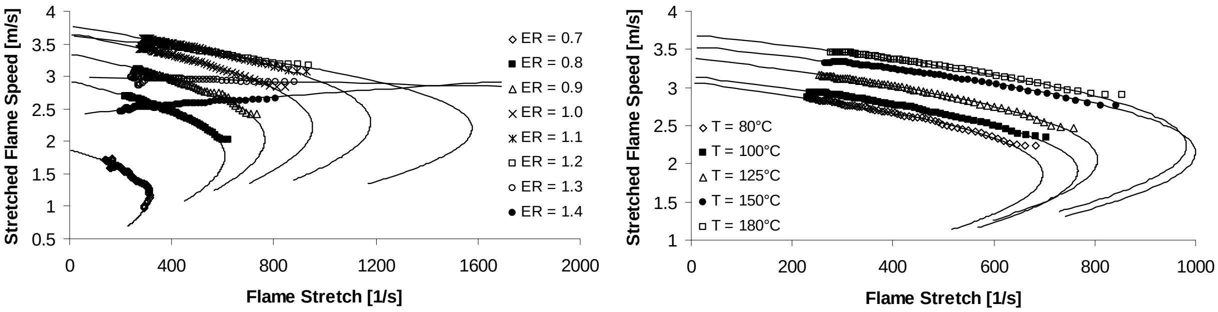


(a) (b)

Figure 2**.** Temporal evolution of the flame radius of a-pinene/air mixture: (a) ER=1 and different temperatures, (b) T=180°C and different equivalence ratios.

Fig. 2.b clearly indicates that there is a linear relationship between flame radius and time in stoechiometric conditions at different temperatures. Slopes of radius-time curves increase with temperature, illustrating the flame speed increase.

Fig. 3.a illustrates the stretched flame speed evolution S_b as a function of the stretch κ at 180°C for different equivalence ratios. Solid lines on these graphs present stretched flame speeds obtained with the nonlinear model solution, taking into account optimization results.



(a) (b)

Figure 3. Stretched flame speed of α-pinene/air mixtures as a function of stretch: (a) T=180°C and different equivalence ratios, (b) ER=1 and different temperatures.

For rich mixtures, there is a good agreement between experimental results and nonlinear model on the linear part of this model. We also observe the slope change for these rich mixtures, indicating the instability of α-pinene flames. The transition occurs from the equivalence ratio 1.3, where the flame speed is almost constant, and therefore independent from the stretch. For lean mixtures, we observe strong nonlinearity; these mixtures are therefore very influenced by the stretch and require the nonlinear extrapolation. The same tendency has already been observed in the literature for iso-octane at 127°C ([17]) and at 80°C ([16]) using the spherical expanding flames technique.

Let us concentrate now on the initial temperature influence on the stretched flame speed as a function of stretch. Fig. 3.b shows that flame speed is increasing when temperature is increasing for stoechiometric mixtures α-pinene/air. For stoechiometric mixtures and whatever the temperature is, the flame speed decreases when the stretch value increases. Similar tendencies has been observed for methanol/air mixtures at 37°C, 87°C and 137°C ([18]) and for propane/air mixtures at 27°C, 97°C and 167°C ([19]).

4 Unstretched flame speeds and comparison with real cases

We are going to deal now with the presentation of the results of unstretched flame speed obtained for different equivalence ratios and different initial temperatures. The flame propagation speeds for three real accidents will be compared to experimental results. There have been many studies on accelerating forest fires accidents over the last decades, but flame propagation speeds are reported just in a few of them. We can note the contribution of [20] for the Palasca accident (Corsica, France) in 2000 where the rate of spread was evaluated around 3.9 m/s. The Freixo accident which occurred in Portugal in 2003 has been simulated with the eruptive fire model developed in [6] and the obtained value was around 3.3 m/s. More recently, a rate of spread around 1.4 m/s has been reported for the Artemida accident (Greece, 2007), [5].

The unstretched flame speeds S_b^0 as functions of equivalence ratio are illustrated on Fig. 4 for different temperatures. The rate of spread values of the three accidents cited above are represented by lines parallel to the equivalence ratio axis. The obtained results show that for each initial temperature, the unstretched flame speeds reach a maximum around $\Phi = 1.1$. These speeds increase when the initial temperature of unburned gases increase. It appears clearly that these experimental unstretched flame speeds are of the same order of magnitude as the real accidents rates of spread reported above. Indeed, if a 10 % error is accepted, α-pinene flame speeds for equivalence ratios between 1 and 1.2 at 180 °C and for equivalence ratios 1 and 1.1 at 150 °C are comparable to the one of the Palasca accident. Concerning the Freixo accident, the rate of spread determined with the eruptive fire model of [6] is in perfect agreement with our experiments at 125 °C near the stoechiometry, and at 150 °C and 180 °C for equivalence ratios between 0.9 and 1.2. Because of the imprecision of the values reported in literature, we can say that the measured values at 80 °C for lean mixtures are in reasonable agreement with the Artemida accident rate of spread.

The results of Fig. 4 show thereby the similarity between the rates of spread of these three accidents and the α-pinene flame speeds measured experimentally. This result enhances the VOCs cloud ignition hypothesis to explain accelerating forest fires ([8], [9], [21]).

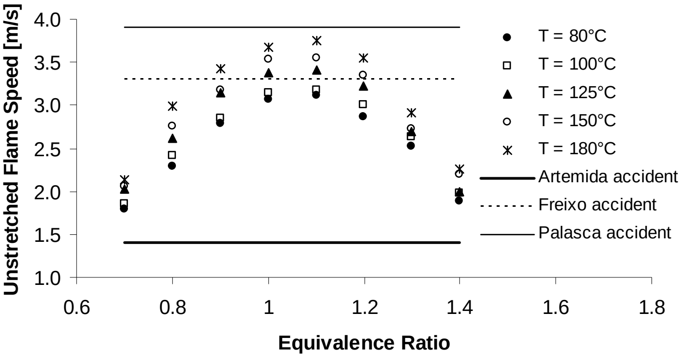


Figure 4. Unstretched flame speeds of α-pinene/air mixtures as functions of equivalence ratio for different temperatures and rates of spread of three real accidents.

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