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A comparative study of the combustion dynamics and flame properties of dead forest fuels

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Abstract

The combustion properties of several dead Mediterranean forest fuels were investigated experimentally. Samples of *straw*, *eucalyptus*, *shrubs*, and *Pinus Pinaster* with the same load were placed in cylindrical containers of the same size and were ignited from the perimeter of the container's bottom. A pitot tube and a thermocouple are placed one meter above the fuel surface to measure the airflow induced by the flame and the flame temperature. The main combustion parameters (mass-loss rate, flame height and temperature, and the induced air velocity) seem to evolve according to the same trend regardless of the fuel type. They increase rapidly in the growth phase of the flame then they decrease over a relatively long period characterizing the decay phase. In the crossover period between these two burning phases, the flame is fully developed with a maximum height and burning rate. The time required for the burning rate to attain its maximum value seems to vary only slightly with the fuel type. The maximum flame height and burning rate are found to be the largest for *shrubs* and the lowest for *straw*. The flame temperature and airflow are found to depend on the position in the flame with maximum values near the continuous zone of the flame.

1. Introduction

The increasing number of forest fires around the globe represents a major concern because it endangers seriously the ecosystem by affecting the flora, fauna, the environment, and even human life (Pausas et al. 2008; Vilén and Fernandes 2011). Therefore, a deeper understanding of the combustion dynamics of forest fuels and a better estimation of their combustion characteristics and their correlations are necessary. Many works were already devoted to examining the behavior of these parameters in the case of pool fires (Zabetakis and Burgess 1961; Tarifa 1967; Kung and Stavrianidis 1982; Babrauskas 1983; Koseki and Yumoto 1988; Koseki 1989; Klassen and Gore 1994; Chatris et al. 2001), fire whirls (Martin et al. 1976; Lei et al. 2011; Pinto et al. 2017), and natural fires (Thomas 1963; Dupuy et al. 2003; Sun et al. 2006; Weise et al. 2005).

In this work, an experimental study of the burning characteristics of several Mediterranean forest fuels is realized where the turbulent diffusion flame is subjected only to buoyancy forces. Samples of dead *shrubs*, *Pinus Pinaster*, *eucalyptus*, and *straw* are placed in cylindrical baskets of the same size and ignited to study the effect of the fuel type on fire behavior. The time evolution of the mass-loss rate, flame's height, temperature, and upward air velocity are examined during all the phases of fire development. A systematic comparison between the combustion characteristics and flame properties of these fuels is realized to study their correlations and their role in the flaming combustion behavior.

2. Experimental setup

The samples with the same fuel load (M_f) and initial height ($34\ cm$) are placed in cylindrical containers (with a fixed diameter $d_c = 0.5m$) made of a metallic grid and open on the top. Before each burning experiment, the fuel moisture content is estimated by using a moisture analyzer A&D MX-50 with a resolution of $0.01\ g$. The relative humidity of air and ambient temperature are measured by a thermo-hygrometer. A thermocouple and a Pitot tube are placed one meter above the fuel surface to determine the flame temperature and air velocity at this height respectively (see Fig.1).

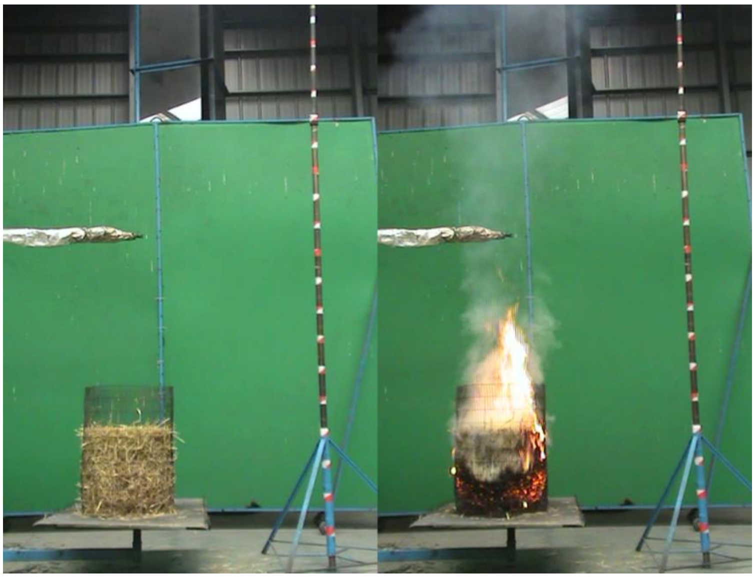

Figure 1. Experimental setup for a straw burning experiment at the Fire Lab of ADAI (Coimbra).

These samples are ignited from the perimeter of the container's bottom under free burning conditions. Three experiments were realized for each fuel to ensure the repeatability of the tests. Each experiment is recorded by an optical video camera Sony FDR-AX53 and a digital camera Canon EOS 550D. The videos are segmented into images by using a Video to JPG Converter software allowing the estimation of the flame heights during the entire duration of flaming combustion. A vertical scale was placed near the container to allow a proper scaling of the flame height values. A digital balance A&D HW-100KGL (10 g resolution) with a frequency of 1 Hz was used to measure the mass evolution of the fuels during their combustion, and its values are recorded on a computer by an RSKey v.1.40 software.

3. Results and discussion

The time evolution of the normalized fuel mass (M_f/M_0, M_0 being the initial mass of the fuel) is shown in Fig.2 for all the fuels considered. The fuel mass decreases towards an asymptotic minimal value M_{fmin}. These curves can be described by the following equation (Drysdal 2011):

$$\frac{\mathrm{d}M_f}{\mathrm{dt}} = -\mathrm{K(T)}.M_f \qquad (1)$$

Where K(T) obeys the Arrhenius law $\mathrm{K(T)} \propto \exp\,(-E_A/\mathrm{RT})$. E_A is the activation energy (J/mol) and R the universal gas constant (8.314J /K.mol). This formula is very simple because it accounts only for the water evaporation accompanied by volatiles emission during the pyrolysis of the fuel. It does not take into consideration other mechanisms such as the scission and formation of molecules (David 1975). Equation (1) is also a relaxation equation that leads to an exponential relaxation if the temperature is constant. The curves shown in Fig.2 seem to exhibit two distinct relaxation regimes. For short times, the fuel mass relaxes very rapidly through time and characterizes the growth phase of the fire. Relaxation becomes anomalously slower during the decay phase of the flame (long times). The crossover between these two processes occurs when the flame is fully developed. Moreover, this tendency to equilibrium seems to depend on the fuel type, it is faster for *shrubs* than for *Pinus Pinaster* needles, *straw*, and *eucalyptus* leaves.

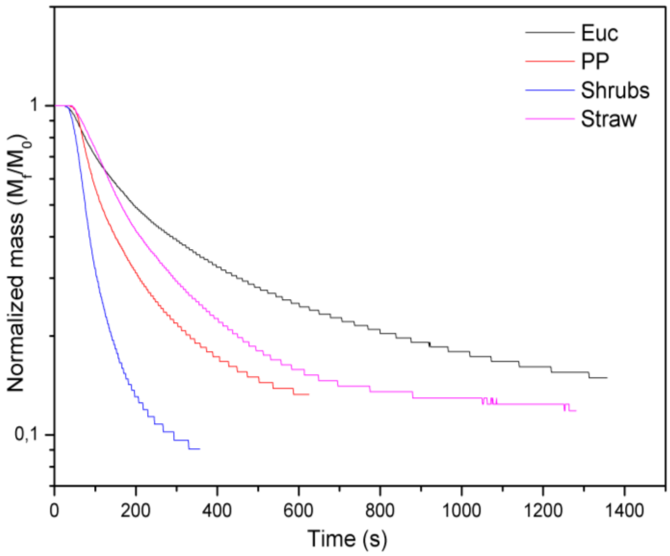

Figure 2. Temporal evolution of the normalized fuel mass for several dead forest fuels.

The mass-loss rate $\dot{M}_f$ is a measure of the rate at which the fuel is consumed, and is a key element to understanding the combustion dynamics. It is deducted from the balance data and its averaged values are estimated at regular intervals (five seconds). The results illustrated in Figs.3 show the same temporal trend for the mass-loss rate, the flame's height, temperature, and the flame-induced air velocity. Fire development is as follows: after ignition, the flame spreads vertically very rapidly along the lateral fuel surface, where a consistent flame begins to form accompanied by a horizontal spread of the flame through the upper surface of the fuel. Afterward, the growth phase begins where the mass loss rate, flame's height, temperature, and upward air velocity increase continuously and the fire uses the available combustible and oxygen to grow until it attains its peak. Then, the flame becomes fully developed and its height is maximum l_{max}. This is followed by a decay of the flame height and mass-loss rate over a relatively long period that characterizes the decay phase. As the thermocouple and pitot tube are placed at the same position to the initial fuel surface, the flame temperature and the vertical motion of gas particles are measured at different relative positions of the flame. Indeed, according to McCaffrey, the flame is subdivided into three regions (McCaffrey 1979):

- The continuous zone that begins at the fuel surface and where the velocity of gas particles increases with height ($v \propto \sqrt{z}$) and the temperature is constant ($T \propto z^0$).
- The intermittent region (the pulsating part of the flame that begins at the end of the first zone) where v is approximately invariant and the flame temperature decreases inversely with height ($T \propto z^{-1}$),
- The thermal plume (situated above the flame) where the gas velocity begins decreasing with height ($v \propto z^{-1/3}$) and the smoke temperature continues falling with height at a faster rate ($T \propto z^{-5/3}$)

Hence, the flame temperature and gas velocity reach their maximum values when the flame is fully developed because they are measured at the closest position to the continuous zone of the flame (see Fig.3a where $l_{max} > 1m$ is much higher than the thermocouple position for all the fuels studied). Since $l < 1m$ in the first part of the growth stage and the last part of the decay phase, the temperatures and velocities measured in these periods are those of the thermal plume and not the flame itself. Therefore, the convection coefficient, which is related to air velocity varies with the vertical position in the flame.

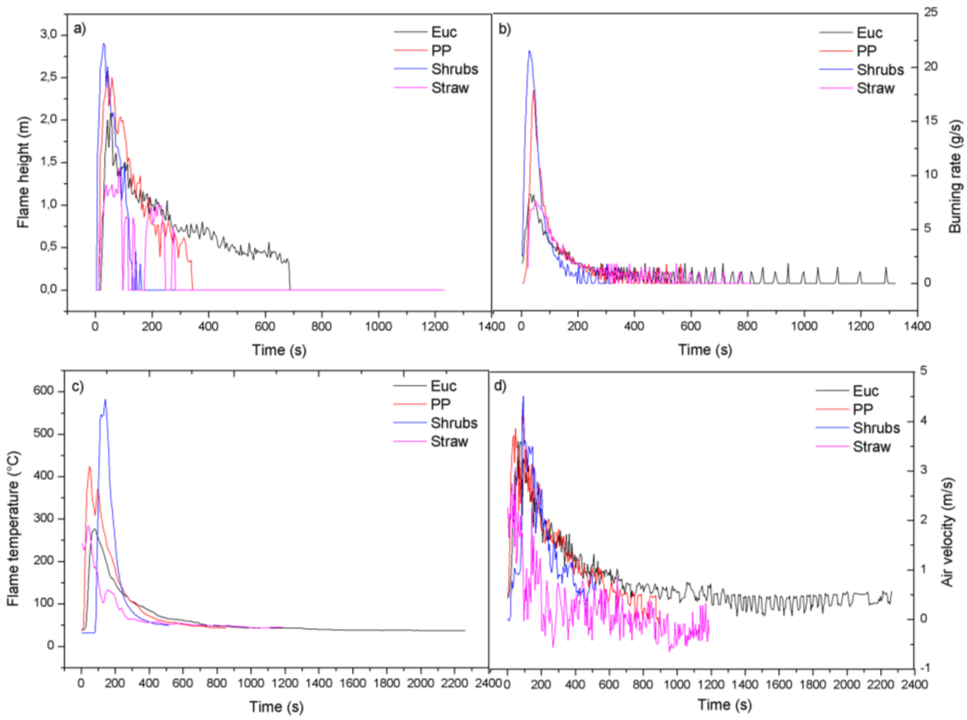

Figure 3. Temporal evolution of: a) flame height (m), b) mass loss rate (kg/s), c) flame temperature (°C), d) air velocity (m/s).

The time t_{max} required for the mass-loss rate to attain its maximum seems to be independent of the fuels $t_{max} = (32.5 \pm 10)$s.There is a time delay Δt between the time at which the burning rate is maximum ($\dot{M}_{fmax}$) and that at which the flame height is maximum (l_{max}). This delay has been found to depend linearly on the fuel moisture content (Sun et al. 2006). The moisture content may not be the only cause of delay since even for completely dried fuels, Δt would still not vanish because of the time required for gas molecules to diffuse through the porous fuel before contributing to the flame. In this work, the moisture content of the samples is around $8 - 10\%$ for all experiments, Δt seems to not change significantly (within statistical errors) for the dead fuels considered (besides a slight increase for straw) as shown in Table 1 where he maximal values of the flame's geometrical and physical characteristics are summarized. The maximum flame height and mass-loss rate are the largest for *shrubs* and the lowest for *straw*. This may be due to the heat flux absorption of the fuel which is related to its optical length, and thus to its packing ratio and surface-to-volume ratio. An extensive analysis of the heat transfer mechanism through the fuels considered is necessary.

Fuel type	Heat of Combustion (kJ/g) [13]	Maximum flame height (m)	Maximum mass loss rate (g/s)	Maximum temperature (°C)	Maximum air velocity (m/s)	Residence time (s)	Δt (s)
Eucalyptus	22.5	1.9 ± 0.3	10 ± 2	292 ± 30	3.9 ± 0.4	845 ± 260	7 ± 6
Pinus Pinaster	13.5	2.5 ± 0.3	18 ± 1	397 ± 19	4.2 ± 0.2	242 ± 83	8 ± 8
Shrubs	16.9	2.9 ± 0.1	24 ± 2	488 ± 78	4.9 ± 0.4	148 ± 35	13 ± 8
Straw	11.7	1.5 ± 0.3	7 ± 1	334 ± 34	3.3 ± 0.4	296 ± 67	25 ± 7

Table 1. Maximum values of some burning characteristics of various forest fuels.

The flaming combustion duration defines the residence time of the flame t_{res}. In Table 1, the maximum flame height (and maximum mass-loss rate) decreases as the residence time t_{res} increases for the fuels considered with a saturation tendency for *Eucalyptus* and *straw*. This is in qualitative agreement with the experimental results found in the case of fire whirls (Pinto et al. 2017). Note the very large residence time of *Eucalyptus*, which is also characterized by a large heat of combustion. Therefore, the total heat released is much larger for *Eucalyptus* leaves despite their heat release rate being smaller than that of *Shrubs*.

4. Conclusion

An experimental study of the burning characteristics of several dead forest fuels was realized. Samples of dead *Eucalyptus*, *Pinus Pinaster*, *straw*, and *shrubs* with the same fuel load were placed in cylindrical baskets and ignited from the bottom. Time evolution of the combustion parameters was found to follow the same trend for all the fuels considered. In the growth phase of the flame, the fuel mass-loss rate, flame's height, temperature, and upward air velocity increase rapidly, then they decrease over a relatively long period characterizing the decay phase. The crossover between these two processes occurs when the flame is fully developed, and the time required for the burning rate to attain its maximal value was found to be the same for all the used fuels. The flame heights and mass loss rate are the largest for *shrubs* and lowest for *straw*. The flame temperature and air velocity seem to depend on the position in the flame, which implies that the heat transfer mechanism varies in the flame.

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