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Determination of the main parameters influencing forest fuel combustion dynamics

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Abstract

This work aims to characterize pine needles as a fuel for a better understanding of the behaviour of forest fuels in wildland fires. It does this in two ways: classify vegetation as a fuel for forest fires, and understand the role of transport mechanisms in fuel beds. For this purpose, the physical and chemical characteristics of each fuel are taken into account. Three species of pine needles were studied: *Pinus halepensis*, *Pinus pinaster* and *Pinus laricio*. These were chosen because they are representative of the Mediterranean ecosystem and present different characteristics such as surface-to-volume ratio and chemical composition.

The experiments were performed using the FM Global Fire Propagation Apparatus with a Fourier Transform Infrared gas analyser to determine the pyrolysis gases released by the three species. The Heat Release Rate (HRR) was estimated using oxygen consumption calorimetry. Specially constructed porous sample holders were used, with different percentages of basket openings, to allow different air flow rates to pass through the fuel samples. Forced flows of different magnitudes were also imposed through the sample in some cases.

In this study, the focus has been made upon the influence of the two main experimental parameters, i.e. flow conditions through the fuel bed (varying with basket opening and forced flow conditions) and fuel species particularities, on the time dependent variable HRR.

Discrete variables such as time to ignition, duration of flames and mean HRR during the flame were also analysed.

Flow conditions appear to be an important parameter when analysing the combustion dynamics of a porous fuel. Fuel species also have an influence on the Heat Release Rate. The role of these parameters and their interaction prove to be more complex than anticipated. Surface-to-volume ratio and fuel packing ratios are not the only parameters governing burning dynamics, even for closely related species such as pine needles. Chemical properties have also proved to have an influence when the oxygen supply in the combustion zone is high.

Introduction

Forest fires behaviour and the mechanisms involved are highly complex. The ability of the forest fire community in modelling and simulating forest fire spread, as well as developing management approaches and techniques, has increased significantly in recent years [1]. Modelling has become an essential tool in forest fire research and is now a crucial instrument in the studies of risk mapping, fire propagation, as well as in forest management. However, to help manage the increasing risks and better understand complex wildland management issues, improved assessment tools need to be developed [1]. Experimental studies are necessary to both calibrate and validate the predictions of models [2]. Fire ignition, fire behaviour, risk assessment and fire mitigation necessitate a thorough understanding of the chemical and physical processes involved in fires. How wildland fuels burn and which parameters have the greatest influence over the combustion process are questions which need to be addressed.

Some tools, which have been developed in older and more mature fields of research, can be applied to these issues. For instance, oxygen calorimetry [3] has been and is still applied with great success in the fire safety community. The Heat Release Rate (HRR) serves to define parameters such as entrainment for fire plumes and flame geometry for open fires [4]. This parameter has been studied recently in both attempts to classify vegetation as a fuel for forest fires [5] and to understand the role of transport in porous fuels beds [6].

A test method used for analysis of any wildland fuel combustion needs to carefully consider the physical and chemical characteristics of the fuel and how the experimental configurations will provide useful data for the circumstances of the data application. Laboratory small scale experiments are valuable in this regard, indeed the smaller the fire, the better the fire parameters can be monitored and controlled. This is the case for many of the fuels relevant to wildland fires, such as pine needles. Pine needles present a clear fire hazard in the Mediterranean region by providing a continuous fuel matrix across the forest floor. Whilst other shrubs, crown fires and tree canopies contribute to wildland fire intensity, the forest floor fuels sustain wildland fires and allow for the greatest extent of fire spread [7]. This property highlights their importance for assessing fire hazards in terms of ignition and spread.

An earlier study provided some calorimetry data relevant to issues associated with wildland fuel characterization [6]. The results showed the applicability and usefulness of calorimetry for this purpose. The test conditions allowed the internal porous fuel bed characteristics to be examined. The results indicated that the transport processes inside the fuel bed have a significant impact on the combustion process within the porous bed. But many questions still remain, particularly regarding the role of physico-chemical properties of species and degradation gases in biofuel combustion.

The work described in this paper presents a further step in fuel bed characterization by testing the role of different species and forced flow magnitudes on the burning dynamics of pine needles. In addition, an analysis of the pyrolysis gases was carried out for three different species to investigate the influence of their chemical properties on HRR. The same kind of fuel was kept for comparison with the previous work. Also, the pine needles used in this work have close but different properties, allowing focusing the study on specific parameters such as surface-to-volume ratios, bed packing ratios and chemical compounds in the fuel.

Experimental apparatus and protocol

The experiments presented in this paper were conducted using the FM-Global Fire Propagation Apparatus (FPA) [8]. Like the cone calorimeter, from which it has kept its operating principle, the FPA allows, among others things, the measurement of the energy released by the combustion of a material by the means of Oxygen Consumption Calorimetry (OC).

The fuel sample is subjected to an external radiative heat flux, and a pilot ignition source is provided. For this study, the radiative heat flux imposed on the sample was 25 $kW.m^{-2}$. The infrared heaters were not shut down after ignition but remained on during the whole test in accordance with standard test procedures [8], this is consistent with actual fire conditions. The mass loss rate of the sample is measured and the exhaust gases are analysed for composition, temperature, optical obscuration and flow speed with a Pitot tube. The FPA allows natural convection or forced gas flow rate through the fuel bed, if a porous sample holder is used. The FPA basic layout is presented in Figure 1.

Custom built porous sample holders were used for the experiments [6]. Indeed, the aim of this work is to study the transport and species effects on porous fuel bed combustion dynamics. The sample holders are circular baskets (diameter: 12.6cm, depth: 3.5cm) made of stainless steel, with holes on all the surfaces (sides and bottom) to allow flow to pass through the bed of pine needles. Three different percentage openings have been tested: 0% (one basket lined with aluminium foil), 26%, and 63%. The sample holders fit inside the combustion chamber, which is cylindrical, and are positioned on a load cell.

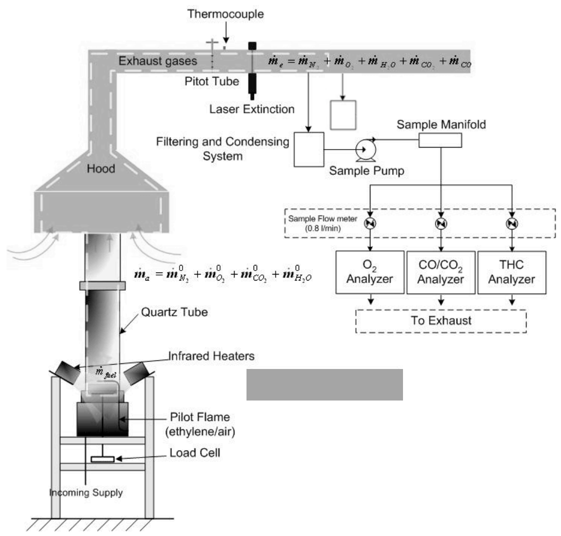


Fig. 1. *Overview of the Fire Propagation Apparatus.*

Three fuels were studied. They were pine needles from three different species, namely *Pinus pinaster* (Pp), *Pinus halepensis* (Ph) and *Pinus laricio* (Pl). The pine needles were collected from Mediterranean wildland areas; they were dead and not conditioned prior to testing. Their moisture levels have been determined by oven drying of a sample for 24 hours at 60°C. The percentage of humidity of the fuel samples ranged between 4.9 % and 6.4 %. The surface to volume ratios of each species were approximately 6500 m^{-1}, 4600 m^{-1} and 3100 m^{-1} for *Pinus halepensis*, *Pinus laricio* and *Pinus pinaster* respectively [9]. The baskets were filled to the top and a constant mass of 15g was used in each test (Fig. 2).

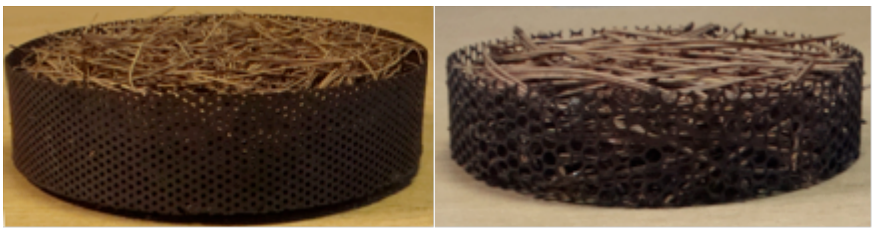


Fig. 2. *Sample baskets – a) Pinus halepensis, 26% opening basket, b) Pinus pinaster, 63% opening basket.*

There were three experimental factors: the fuel species, the basket percentage opening and finally the convection conditions (natural (NF) and two conditions of forced flow: Low Flow (LF) - 100 $L.min^{-1}$ and High Flow (HF) - 200 $L.min^{-1}$). The precise value of the flow through the fuel bed samples was not directly measured, as the sample holder was a bit smaller than the combustion chamber. It was estimated, by Particle Image Velocity (PIV) of a non-reacting flow, that 15-35 % of the flow went through the sample holder, depending on the different species and baskets [6]. Each test conditions were repeated between three and six times.

Another set of experiments was performed to determine pyrolysis gases from the three pine species. These experiments were also conducted using the FPA but, in addition, a Fourier Transform Infrared (FTIR) gas analyser [10] was connected to the exhaust duct of the device (see Fig.1). Infrared spectroscopy is a technique for chemical analysis and determination of molecular structure in solid, liquid and gas state. The principles that molecular vibration occurs in the infrared region of the electromagnetic spectrum and functional groups in chemical compounds have characteristic absorption frequencies are the basis of this technique [10]. The sample mass in these tests was 4 g and the heat flux imposed to the sample was the same as for the combustion experiments (25 $kW.m^{-2}$). A nitrogen flow (60 $L.min^{-1}$) was passed through the sample and a quartz tube was connected to the combustion chamber to create a non oxidative atmosphere (see Fig. 1). After each test, the remaining mass of char was measured.

Calorimetric calculations

OC is a convenient and widely used method for measuring the amount of energy release on a laboratory scale fire test. When estimating the Heat Release Rate (HRR) of a reaction from the chemical species concentration, the main hypothesis relies on the knowledge of the evolution of the combustion gases during the reaction. The stoichiometric reaction for the complete combustion of a chemical compound $C_xH_yO_z$ is given by [11]:

$$C_xH_yO_z + \left(x + \frac{y}{4} - \frac{z}{2}\right)\left(O_2 + 3.76N_2\right) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76\left(x + \frac{y}{4} - \frac{z}{2}\right)N_2 \tag{1}$$

OC comes from the observation made that, for a large number of fuels, the energy released per unit mass of oxygen consumed can be considered as a constant: Huggett's constant (E) which is 13.1 $MJ.kg^{-1}$ of oxygen consumed. In general, several simplifying assumptions are made: all gases are considered to behave as ideal; the analysed air is only defined by its composition in O_2, CO_2, CO, H_2O and N_2. All the other gases are assimilated with N_2; gases are analysed for a dry air, water vapour being removed because the analysers are sensitive to moisture. OC principle expresses HRR as:

$$\dot{q} = E\left(\dot{m}^{\circ}_{O_2} - \dot{m}_{O_2}\right) \tag{2}$$

where $\dot{m}$ is the mass flow rate ($kg.s^{-1}$), the superscript ° indicating that the measured value is taken before combustion.

From the data given by the FPA, the HRR can be obtained as follow. The mass flow rate of the exhaust gases ($\dot{m}_e$) is determined using the Pitot tube. The parameter ϕ, defined as the depletion factor, is the fraction of the incoming air that is fully depleted of its oxygen during the combustion process. It is given by the expression below:

$$\phi = \frac{\left(\dot{m}^{\circ}_{O_2} - \dot{m}_{O_2}\right)}{\dot{m}^{\circ}_{O_2}} \tag{3}$$

Considering that $M_e \approx M_a$ (exhaust and incoming air molecular weights ($g.mol^{-1}$)), and assuming N_2 to be conserved (as it does not participate in the combustion reaction), the exhaust mass flow rate can be linked to the incoming one by:

$$\dot{m}_a = \frac{\dot{m}_e}{1+\phi(1-\alpha)} \tag{4}$$

where α is the expansion factor.

During combustion, a fraction of the incoming air is depleted of its oxygen and is replaced by an equal or larger number of moles of combustion products, the expansion factor is the ratio of these two molar quantities. To simplify the calculation, an average value for α is assumed to be equal to 1.105 with a maximum relative error of 10% [12]. In addition, the value of E has been estimated considering a complete reaction, when CO production cannot be considered as negligible anymore, it becomes necessary to correct this value taking into account the amount of O_2 necessary to oxidize CO into CO_2. Equation (2) becomes:

$$\dot{q} = E\left(\dot{m}^{\circ}_{O_2} - \dot{m}_{O_2}\right) - \left(E_{CO} - E\right)\left(\Delta\dot{m}_{O_2}\right)_{cat} \tag{5}$$

where E_{CO} is the energy released by unit mass of CO generated and with the variation in O_2 mass flow rate being:

$$\Delta\dot{m}_{O_{2cat}} = \frac{(1-\phi)}{2}\frac{X^A_{CO}}{X^A_{O_2}}\frac{M_{O_2}}{M_a}\dot{m}_a X^{A^\circ}_{O_2} \tag{6}$$

the superscript A indicating the analyser values.

Knowing that the measures are made on a dry air, equation (5) can be rewritten as follows:

$$\dot{q} = \left(E\phi - \left(E_{CO} - E\right)\frac{1-\phi}{2}\frac{X_{CO}^{A}}{X_{O_2}^{A}} \right)\frac{\dot{m}_e}{1+\phi(\alpha-1)}\frac{M_{O_2}}{M_a}\left(1 - X_{H_2O}^{\circ}\right)X_{O_2}^{A\circ} \tag{7}$$

As described above, HRR is not obtained directly, but computed from many variables. For each measured value an uncertainty is associated, which reflects in the mathematical function giving the HRR [13]. Those uncertainties are of two kinds [13]: Due to experimental measurements (analysers' uncertainties) and due to the hypotheses made (the most important one being the presumed calorimetric coefficient *E*; when the fuel composition is known, a more accurate value can be used [11, 13]). In this study, no corrections have been made to reduce this uncertainty.

Results and discussion

In this section, the focus is made upon the influence of the two main experimental parameters – flow conditions through the fuel bed (varying with basket openings and forced flow conditions) and fuel species particularities – on the time dependent variable HRR. Discrete variables such as time to ignition, duration of flames and mean HRR during the flame are also analysed.

Both flow conditions and fuel type proved to have an effect on combustion dynamics. Initially, their influence will be examined separately, then their cross interactions will be investigated.

Flow influence

In order to illustrate the burning behaviour of the pine needles during the tests, the mean discrete values for time to ignition and flame duration will be presented as well as the mean heat release rates produced by their combustion for every experimental condition.

Table 1 shows times to ignition for *Pinus halepensis* under the different experimental conditions. Ignition times are shorter in no flow conditions than in forced flow, and in this case the basket percentage openings do not seem to have a great influence. The combustion gas mixture is fuel rich, the small decrease on time to ignition with higher basket percentage openings may be due to a better supply of O_2. On the contrary, in forced flow, the ignition is delayed, and the basket openings have an influence on the time to ignition. In this case, ignition was difficult to obtain (particularly with the 63% opening basket) and auto-ignition has been observed as, in some tests, the fuel bed ignited remote from the pilot flame. The forced flow through the fuel bed diluted the pyrolysis gases in air and thus led to fuel lean conditions, bringing the mixture under the lower flammability limit. Qualitatively, the results are the same for *Pinus pinaster* and *Pinus laricio*.

Table 1. *Pinus halepensis* time to ignition related to basket opening and flow conditions.

Experimental conditions	Mean Time to Ignition	Standard error
Ph 0 NF	27 s	1 s
Ph 26 NF	24.2 s	4.3 s
Ph 63 NF	20.8 s	3.3 s
Ph 26 HF	72.2 s	3.3 s
Ph 63 HF	139 s	13.8 s

The duration of flaming decreases when the flow allowed through the fuel bed increases, tending towards 25 s irrespective of which species is considered (Fig. 3).

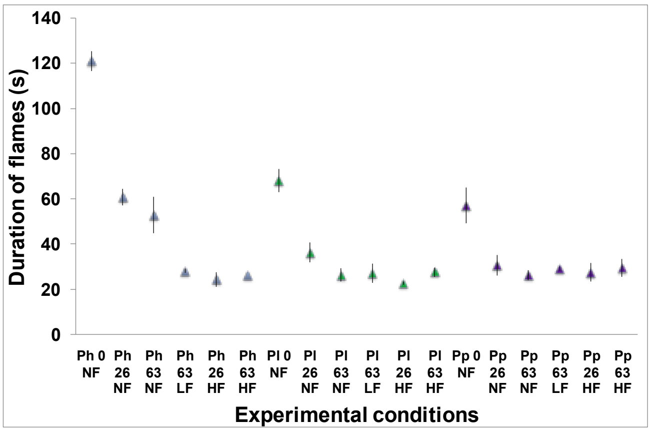


Fig. 3. *Mean duration of flame with associate standard deviation for Pinus halepensis, Pinus laricio and Pinus pinaster.*

The minimal duration of flaming was observed when forced flow was applied. The relationship between duration of flaming and flow magnitude can be linked to the relationship between HRR and flow magnitude, as the total amount of energy which is released is almost constant (only for no flow conditions and with the 0% percentage opening basket a few char remain, in addition, CO and soot concentrations measured during combustion were really low.). The main part of the total energy is released in a shorter time, leading to higher HRR curves.

In figure 4, the results for *Pinus halepensis* are presented as an example. The curves start very close to ignition time, which is given by the sharp increase in HRR

The combustion behaviour is strongly influenced by the flow conditions. The more the flow is allowed to pass through the sample, the higher the HRR curves. When a flow is imposed through the fuel bed sample, flaming combustion and smouldering occur at the same time, leading to higher instantaneous HRR values than in natural convection where those phenomena are distinct. In natural convection, the basket opening has an influence on HRR, which is not observed when a forced flow is imposed to the sample (26HF and 63HF HRR curves are quasi-equivalents).

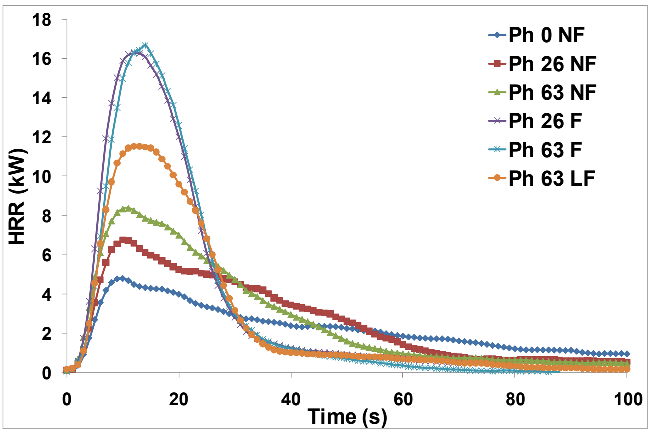


Fig. 4. *Pinus halepensis mean heat release rates for different basket opening and flow conditions.*

Above a given intensity, the flow seems to bring enough oxygen to enhance combustion, irrespective of the basket opening. The tendency is the same for all three species. Experiments were performed with different magnitudes of flow to determine when an increase in the flow does not lead to an increase in HRR. It appeared that this depends on the fuel species, which is consistent with the duration the flame presented in Fig.3. It will be described in the following.

Species influence

Figure 5 and 6 show the influence of the fuel species on the HRR, for no flow conditions.

The behaviour for one experimental condition varies widely with the species. In Fig. 5, the three different pine types demonstrate similar combustion dynamics even if the curves are of different magnitude.

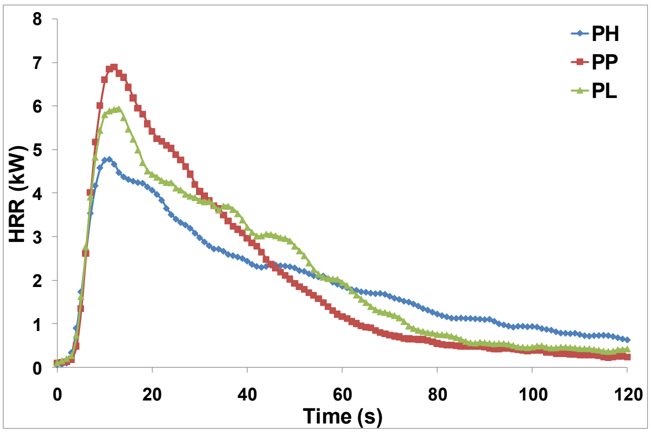


Fig. 5. *Mean heat release rates for the three pine species under no flow conditions and with the 0 % opening basket.*

Duration of flaming proved also to be different (see Fig. 3 for 0 NF conditions), *Pinus halepensis* having the longest burning time and *Pinus pinaster* the shortest one.

The higher the surface-to-volume ratio, the lower magnitude of the HRR curve. This surprising result could be due to mean penetration distance of radiation, *Dr*, of the fuel bed. The radiation received by the fuel bed (coming from the flame and the infrared heaters during the whole test) do not penetrate the bed in the same way according to the geometrical species characteristics. The main geometrical characteristic, which differs between species, is surface to volume ratio, as seen previously. This leads to different responses to convective heat transfer, but also to radiative transfer. The mean penetration distance of radiation is given by:

$$Dr = \frac{4}{\gamma * \sigma} \quad (8)$$

where γ is the volume occupation rate in the fuel bed $\frac{\rho_{fuelbed}}{\rho_{needles}}$ and σ is the surface to volume ratio of the pine needles (m^{-1}) [14].

The results values of *Dr* for the three species are presented in Table 2. *Pinus halepensis* has the smallest mean penetration distance of radiation resulting in lower radiative transfer through the bed, and *Pinus pinaster* the highest one, see table 2. The tendencies of HRR magnitude and flaming duration follow the *Dr* increase. This result needs to be confirmed in other experimental conditions.

Table 2. Mean penetration distance of the radiation for the three species.

Species	*Dr* (*mm*)
Pinus halepensis	12,4
Pinus laricio	12,9
Pinus pinaster	19,4

In Figure 6, *Pinus pinaster* and *Pinus laricio* HRR trends change and look similar except that the *Pinus laricio* HRR curve is now higher than the *Pinus pinaster* one. On the contrary, *Pinus halepensis* combustion behaviour remains the same as in Figure 5, with a longer duration of combustion and smaller instant values of heat released than the two other species.

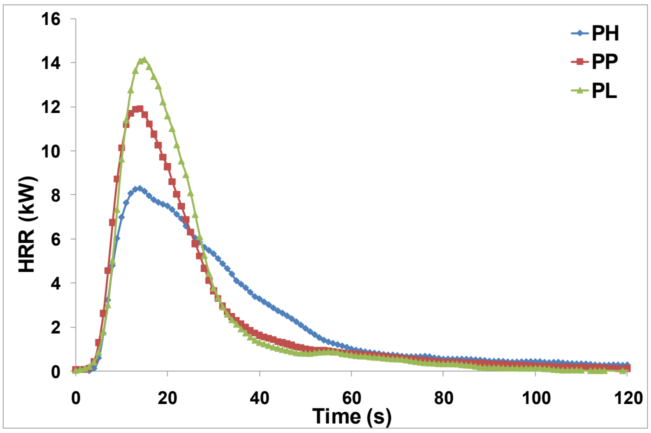


Fig. 6. *Mean heat release rates for the three pines in no flow conditions and with the 63% opening basket.*

Pinus halepensis duration of flaming is still more important than *Pinus laricio* and *Pinus pinaster* ones. According to their different fuel packing ratio, the magnitude of flow needed to reach the minimal duration of flaming differs; *Pinus halepensis* needing the highest one and *Pinus pinaster* the lowest one (see Fig.3).

Fuel bed densities due to geometrical species properties explain the results for *Pinus halepensis* but this is not sufficient to explain the inversion between *Pinus pinaster* and *Pinus laricio*. Thus, other species characteristics, such as chemical ones, need to be taken into account. They will be investigated in the following section.

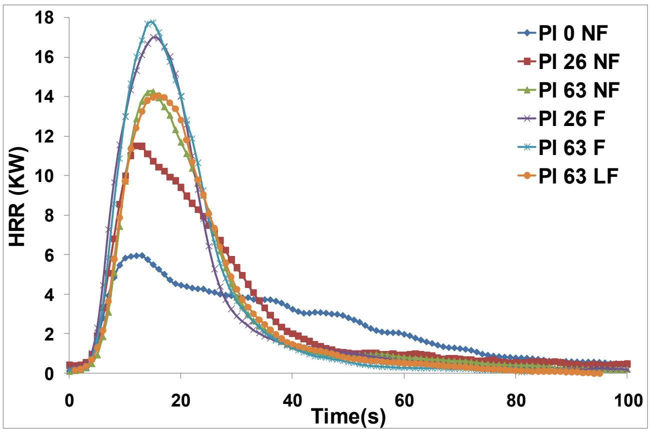
An integration of HRR curves has been done to obtain the total energy released during combustion. The flow conditions do not have an influence on the energy released by *Pinus pinaster* and *Pinus laricio*. Only ashes remained in the sample basket after the tests (around 0.35 g). This is not so true for *Pinus halepensis*; the total amount of energy released for this species is significantly higher in forced flow than in natural convection. In spite of a higher residence time, the combustion of *Pinus halepensis* needles was not complete under natural convection and low basket percentage openings (in many cases, some needles were not completely burned at the end of the experiment), which was not the case for *Pinus pinaster* and *Pinus laricio*. This is consistent with the observation made by Mendes-Lopes et al. [2] when studying fires propagating in beds of *Pinus halepensis* needles.

Determination of the parameters driving the combustion dynamics

Flow conditions through the porous fuel bed and fuel species have both an influence on burning dynamics of pine needles. This section will investigate which fuel species property plays a dominant role according to flow conditions.

Figure 7 shows the mean HRR for *Pinus laricio* and *Pinus pinaster* under every experimental condition. *Pinus halepensis* has been already presented in Fig. 3. The HRR behaviour in response to the flow magnitude varies from one species to the other.

a)



b)

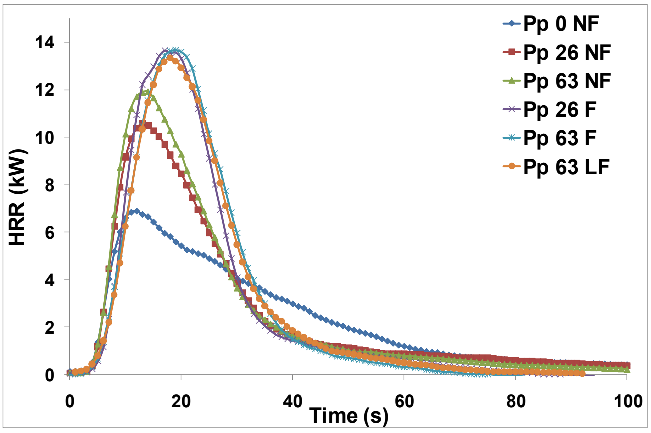


Fig. 7. *Mean heat release rates for different basket opening and flow conditions – a) Pinus laricio and b) Pinus pinaster.*

For *Pinus halepensis*, the gap between no flow and flow conditions is the most important. The fuel bed drag forces seem to be the main parameter that can be only overwhelmed by a forced flow through them. The fuel beds of *Pinus laricio* and *Pinus pinaster* are less compact than for *Pinus halepensis*, their pine needles are bigger than *Pinus halepensis* ones, inducing bigger gaps inside the fuel bed and allowing more flow passing through them (see Fig.2 for

Pinus halepensis and *Pinus pinaster*). This leads to a higher influence of the basket opening on the results (see Figs. 7 a and b) than with *Pinus halepensis*.

Duration of flaming is also linked to the fuel species (see Figs 4 and 6). Even if the trend is the same for the three species, they show different sensitivities to this external influence. The relationship between duration of flaming and flow magnitude can be linked to the relationship between HRR and flow magnitude. Again, forced flow dominates basket opening conditions, sooner or later, according to internal fuel bed resistance to the flow and percentage basket opening. *Pinus halepensis* appears to be more sensitive to flow conditions than *Pinus pinaster* and in a smaller proportion than *Pinus laricio*. With the 100 $L.min^{-1}$ forced flows, the maximum HRR is already obtained for *Pinus pinaster* but not for *Pinus halepensis*. The variation in experimental results for Pinus laricio do not allow conclusions to be drawn, but it seems that the maximum HRR is not already obtained for the100 $L.min^{-1}$ forced flow. Furthermore, flow increase seems to have a cooling effect on *Pinus pinaster* combustion. Figure 6 c shows that the burning is delayed when increasing the flow conditions as the time to Peak HRR increases. Once again, fuel bed density due to geometrical species properties seems to drive the results.

The time average values of HRR during the flaming stage are presented in Figure 8. They increase with the flow but not in the same proportions, leading to an inversion between the species when increasing the flow.

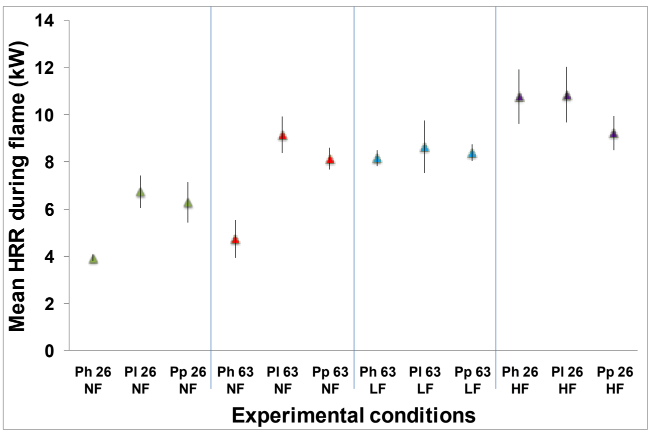


Fig. 8. Time average HRR during the flame for the three pine species

In natural convection, *Pinus laricio* and *Pinus pinaster* release more energy than *Pinus halepensis*, because their geometrical properties allow the oxygen to pass through the bed sample more efficiently. On the contrary, when the flow magnitude is sufficient enough, oxygen limited conditions are avoided inside the reaction zone and the geometrical properties alone cannot explain the changes in tendencies. The inversion in tendency, with increasing the flow, may be found in the chemical properties of the species.

To investigate the contribution of the chemical compounds in the combustion dynamics, pyrolysis experiments were conducted in a nitrogen atmosphere. A FTIR gas analyser was used, in addition to the FPA ones, to determine the different compounds in the degradation gases and their magnitude for each species. To validate the new device, *CO* concentrations were measured at the same time by both devices (FPA and FTIR), showing consistent results as presented in Figure 9.

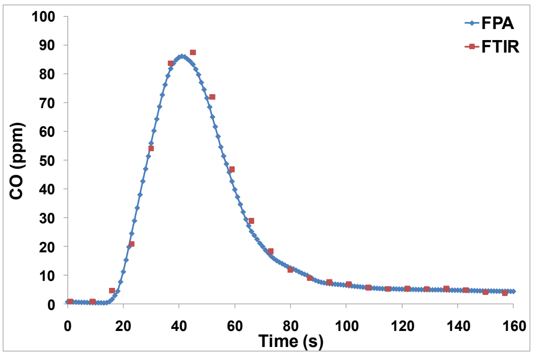


Fig. 9. *CO concentration for Pinus pinaster during pyrolysis experiments.*

For the three pines, the amounts of char obtained at the end of the experiments were the same, i.e. approximately 73% of the mass was lost during the pyrolysis stage leading to 27% of char. FTIR results showed that the main combustible gases for the three species were: Carbon monoxide (CO), Methane (CH_4), Ethylene (C_2H_6), Formaldehyde ($CHOH$), Hexane

(C_6H_{14}), Benzene (C_6H_6) and a lower amount of heavy hydrocarbons such as Ethyl benzene (C_8H_{10}). The quantities released by each species during pyrolysis are given in Table 3.

Table 3. Pyrolysis gases released by the three species in *ppm*.

	Pinus halepensis	*Pinus laricio*	*Pinus pinaster*
CO	411.07	406.33	507.64
CH_4	140.3	147.26	143.19
C_2H_6	111.5	153.18	131.9
$CHOH$	99.36	110.71	107.14
C_6H_{14}	62.12	66.88	55.75
C_6H_6	21.21	33.63	34.75
C_8H_{10}	16.03	89.98	62.94

A calculation including the heat of combustion of each chemical compounds has been made, with concentrations given in Table 3, to determine which species release the most energetic gas mixture. This can be done since those compounds are fully oxidized during the combustion (CO concentrations during the flame are negligible regarding CO_2 ones [6]). It has been found that the *Pinus laricio* pyrolysis gases composition yields the highest heat of combustion. Those results are consistent with a previous study made to analyse pyrolysis gases for the three species, and with their Low Heating Values (LHV) given in Table 4 [15].

Table 4. Low Heating Value for the three pine species [15].

Species	LHV ($kJ.kg^{-1}$)
Pinus halepensis	18274
Pinus laricio	19299
Pinus pinaster	17720

When flow is imposed, the three species have the same duration of flaming and their combustion is almost complete. Smouldering and flaming combustion occur at the same time, leading to a mass loss during the time of flaming of approximately 90 % of the initial mass. The species having the higher LHV are the ones releasing more energy during flaming. The chemical composition of pine needles seems to become prevalent.

Conclusions

This study shows that flow conditions through the porous fuel bed and fuel species both have an influence on the burning dynamics of pine needles, and cross interactions have been presented. The role of these parameters proved to be more complex than anticipated. Indeed, the relative importance of the chemical influence compared to the geometrical properties has been highlighted by the addition in the study of a third species, *Pinus pinaster*. Surface-to-volume ratio and fuel packing ratios are not the only factors governing the burning dynamics, even for similar species as pine needles. When the oxygen supply is sufficient, fuel species chemical properties play a prevalent role. During this study, it has been observed that the EO_2 constant value used in this study for HRR calculations proved to be inaccurate for pine needles and leads to higher HRR than expected with LHV. This value will need to be refined in a future study. Other experimental conditions, such as radiative heat flux or flow magnitude, also need to be tested to generalize the results.

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