



Influence of Compactness on Flammability and Combustibility of Wildland Fuels

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Abstract

Using a cone calorimeter for small-scale tests as a radiant heat source, the influence of compacting fuel beds on their flammability and combustibility for three different types of dry vegetation (*Pinus halepensis* and *Pinus pinaster* needles, and *Wheat straw* sticks) was experimentally investigated for a wide range of compactness (the degree of densification of the fuel bed) from 3 to 50 %. While the flaming duration increases monotonically with packing ratio (a quantitative measure of this compactness), ignition time shows at least one minimum value for the fuels studied. Using the mean free path of radiation as the controlling parameter instead of the packing ratio the range with minimum ignition time is significantly narrowed down to a few millimeters, which indicates the importance of radiation in the flammability process as expected for such a mainly radiative heating process. For *Pinus halepensis* needles, two minimum ignition times for values of packing ratio around 12.6% and 34% were identified both when the fuel bed thickness is varied or maintained constant. For low compactness, before ignition, the mass loss decreases linearly with time with a rate slightly affected by the packing ratio. After ignition, the flame spreads quickly to cover the entire fuel bed (fully developed flame) at the growth time. This marks the beginning of a sharp decrease in the mass corresponding to a sharp increase in the mass loss rate (MLR) towards a maximum value. For high compactness, the linear decrease of the mass still holds before ignition, followed by a long slightly non-linear trend corresponding to the slow flame spreading to cover the whole surface of the bed at the growth time (fully developed flame). This also marks the beginning of a sharp mass decrease (MLR increase). The duration between ignition time and growth time is then very short for low compactness, and becomes very large for high compactness and corresponds to a plateau of MLR. The peak MLR is followed by a slow decrease until extinction (decay phase). To analyze the compactness induced combustion, the MLR curve was divided into two widths: the upper width is the Full Width at Half Maximum (FWHM), and the lower width is the duration (x_t) between extinction time and growth time. The peak MLR, and the FWHM were found insensitive to the compactness (constant behavior within statistical errors for all compactness) whereas the x_t was found to decrease for high compactness.

Keywords Ignition time · Flaming duration · Packing ratio · Mass loss · Mass loss rate

Nomenclature

δ	Mean free path (<i>m</i>)
$\rho_{i=p,fb}$	Density (<i>kg/m³</i>)
σ	Full Width at Half Maximum (FWHM) (<i>s</i>)
ϕ	Packing ratio
D	Holder diameter(<i>cm</i>)
$e_{i=p,fb}$	Thickness (<i>m</i>)
m	Mass (<i>kg</i>)
MLR	Mass loss rate
Ph	<i>Pinus halepensis</i>
Pp	<i>Pinus pinaster</i>
q_{inc}	Heat flux (<i>kW/m²</i>)
SVR	Surface-to-Volume Ratio (<i>m⁻¹</i>)
$t_{i=ign,res}$	Time (<i>s</i>)
W_s	Wheat straw

Subscript

Fb	Fuel bed
Ign	Ignition
Inc	Incident
P	Particle
Res	Flaming (flame persistence)

1 Introduction

Despite the existing scientific knowledge and technical capacity, the erratic behavior of wildland fires that is observed around the world remains a challenge. The understanding of fire behavior requires the knowledge of the role of some fundamental properties such as fuel's physical (density, surface-to-volume ratio, etc.) or thermo-chemical properties, such as the thermally induced degradation and chemical reactions, as a step to better understand and predict the role of environmental factors like weather, land topography, and spatial arrangement of the wildland and the interaction of the fire and its environment [1–3].

The random arrangement of fuel particles in wildland porous fuel beds causes substantial ignition time fluctuations, which were found to be responsible for the probabilistic ignition behavior observed for low values of the incident heat flux [4]. These arrangements can be controlled by the compactness of the fuel bed. The fuel bed compactness was found to affect non-monotonically the rate of fire spread for cribs and excelsior [5] as well as for cardboard fuels [6]. However, this optimum packing ratio (maximum rate of spread) observation in Rothermel model development experiments was obtained based on experiments in which fuel load and fuel bed height and compactness are all varied simultaneously. Hence, the observed non-monotonic relationship between packing ratio and the rate of spread cannot be attributed solely to compactness, as other factors were also varied. This provides an addi-

tional motivation to properly explore the inter-related influence of fuel load, compactness, fuel bed thickness etc.

Recently, ignition time was found to behave monotonically either with the fuel bed density [7, 8], or the permeability or sample holder openings [6, 9, 10]. However, these studies were restricted to a fairly narrow range of packing ratios ranging from 2% to 6% [5–9]. It is then crucial to investigate the effect of compactness on fuel ignitability for a wider range of packing ratios and observe the behavior of ignition time which is the aim of the present work.

In this work, the term compactness refers to the degree of densification and structural arrangement of the fuel bed. This property is quantitatively characterized by the packing ratio, ϕ , which is the average volume percentage of the particles in the fuel bed, and is defined as the ratio of the fuel bed's apparent density ρ_{fb} to the solid density ρ_p of the fuel particles [5]:

$$\phi = \frac{\rho_{fb}}{\rho_p} \quad (1)$$

The packing ratio, which ranges from near zero for very porous fuels to unity for solid fuels, is the primary quantitative metric used in this work to assess the effect of compactness on flammability and combustibility.

A cone calorimeter is used to study the effect of compactness on the ignitability and combustibility of three selected porous vegetation fuels: *Pinus halepensis* (Ph), *Pinus pinaster* (Pp), and *Wheat straw* (Ws). The fuels (dead or alive), representative of surface or canopy wildland fuels, were collected and investigated both in Oran-Algeria (at the Laboratory LEPM/USTO-MB) and in Coimbra-Portugal (at the Laboratory of ADAI/Coimbra University). This study is extended to a larger range of values of the packing ratio (up to 50%) than previous studies, to answer the question of whether the trend of ignition time is monotonic or not. To investigate the sensitivity of fire behavior to fuel bed thickness, tests with *Pinus halepensis* fuels were carried out in two ways: (i) by varying the sample thickness, and (ii) by keeping the sample thickness constant.

2 Methodology

The influence of a wide range of packing ratios (up to 45%), representative of the ground fuels and canopy fuels, on flammability and combustibility is investigated experimentally, using a small scale cone calorimeter under an incident heat flux of 17.5 kW/m². This value was selected to probe the fundamental ignitability of the fuel beds under a significant but sub-maximal radiant heat, which allows for clear observation of the pre-ignition processes and is representative of scenarios involving radiant ignition from a moderate distance or a smoldering source. This approach is common in fundamental studies of ignition thresholds and dynamics, as it amplifies the observable differences between fuel bed configurations [4]. It also allows us to isolate the effects of compactness without the process being dominated by extreme external heating, which can overwhelm the subtle differences we are investigating.

This study was organized into two phases: (i) The first one, was realized at the Laboratory LEPM/USTO-MB in Oran-Algeria, where completely dried live *Pinus halepensis* (Ph) needles were used for ignition tests. The packing ratio was varied by varying fuel bed mass and/or thickness as a first step of the investigation, and by varying the fuel bed load and keeping its thickness constant as a second step. (ii) The second phase, was realized at the Laboratory ADAI/Coimbra University in Coimbra-Portugal, where the dried *Pinus pinaster* (Pp), and Wheat straw were used for ignition, by varying the fuel bed mass and/or thickness.

This study aims to check the trend of ignition time for a such wide range of packing ratios.

2.1 The Studied Parameters

- The ignition time and flaming duration for all selected fuels in case of varying thickness, and for *Pinus halepensis* (Ph) in case of constant thickness and varying load.
- The growth time at which the flame covers the entire fuel bed surface, after spreading from ignition (which is called fully developed flame). This time is used to study the shape of the mass loss rate.
- The mass and mass loss rate (MLR) variation for *Pinus halepensis* (Ph) needles in case of varying thickness
- To check the sensitivity of the MLR to the packing ratio, its shape is divided into two widths (see Fig. 1):
 - The upper width was analyzed using the Full Width at Half Maximum (FWHM, σ), used to describe the width of a peak. It is defined as the distance between the two points on the MLR curve where the MLR reaches half of its maximum value.
 - The lower width (x_t) was analyzed using the difference between the flame extinction time and the growth time.

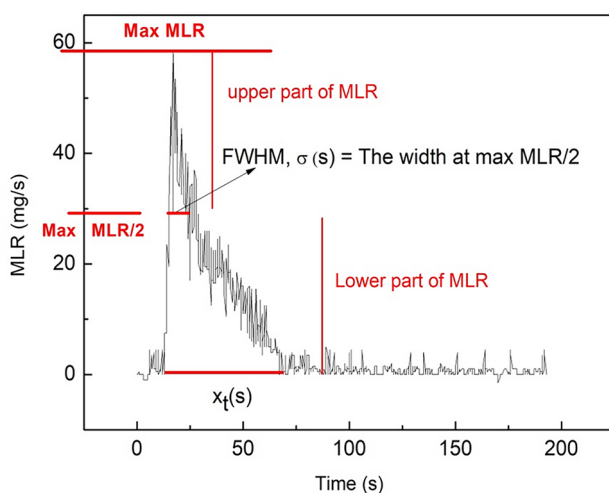


Fig. 1 MLR shape analysis description

3 Experimental Setup

3.1 Cone Calorimeter

The heater of a cone calorimeter, built according to the standards ASTM 1354 [11] and ISO 5660 [12], has a spiral shape with an electrical resistance of 13Ω , delivering 3 kW (nominal power) under 230 VAC (for LEPM's cone), and of 17.3Ω , delivering 4 kW (nominal power) under 230 VAC (for ADAI's cone). It supplies continuously a constant radiative heat flux that causes the fuel bed temperature to rise and may lead to ignition. For a given electrical power, the heat flux delivered by the cone calorimeter on the fuel sample depends on the distance between the top surface of the sample and the last (bottom) spire of the heater. The experimental setup that is schematized in Fig. 2a differs from the standard cone calorimeter which has a constant distance between the cone and the sample. To check the uniformity of the incident flux, the ratio of the heat flux intensity measured at the center of the sample to the average of the flux intensities measured at the edges of the sample was found to vary from 1.006 to 1.04, for distances ranging from 2.5 cm to 15 cm. This ratio remains smaller than 1.06 and meets the standard cone calorimeter uniformity requirement. The incident heat flux is calibrated for the cone calorimeter of ADAI/Coimbra University using a Vattel TG1000-1 heat flux sensor with a range of 0 – 50 kW/m² (with 3% accuracy). A water-cooled sensor of type Hukseflux SBG 01 functioning in the range 0 – 200 kW/m² (with 6.5 % accuracy) is used in the LEPM/USTO-MB cone calorimeter. In Fig. 2b, the calibration measurements reveal a linear trend of the measured heat flux on a semi-logarithmic scale, indicating an exponential decrease with distance.

3.2 Test Details

The ignitability and combustibility of the fuel beds were measured for an incident heat flux of 17.5 kW/m². A small pilot flame (not exceeding 5 mm in length, see Fig. 2a) was used instead of the standard electric spark igniter. This deviation from the ISO 5660 standard was made to better simulate piloted ignition conditions relevant to wildland fires and to ensure reliable ignition of the natural, heterogeneous fuel beds. The flame was positioned

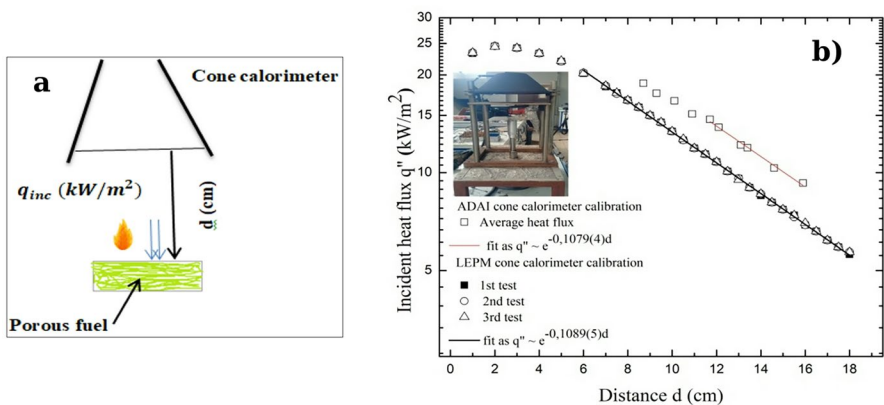


Fig. 2 a A schematic representation of the experimental setup, b calibration of the cone calorimeters at Coimbra and Oran

approximately 1.2 cm above the fuel bed surface close to the 1 cm required by the standard cone calorimeter.

The period between the exposure of the fuel bed and the first appearance of flame is defined as the ignition time. This definition differs from the standard cone calorimeter, according to which ignition occurs when the entire surface is flaming, defined here as the growth time (see the section methodology). These two definitions amount to a one-second difference for low compactness, which is within statistical uncertainty. However, this difference may be very large for high compactness as shown below. If the flame persistence period is higher than 4 s (sustained ignition), the ignition test is declared successful [13]. It fails, on the other hand, if smoldering combustion is observed instead of flame combustion, with complete oxidation of the fuel in its solid phase [14]. The interval between ignition and flame extinction defines the flaming duration. In the case of *Ph* needles and varying thickness, a digital balance KERN PCB with an uncertainty of 1 mg is used to record the mass loss during combustion via data acquisition software KERN. The mass loss rate (*MLR*) was estimated from the derivative of the mass loss within 1/3 (s). For repeatability, at LEPM/USTO-MB, at least fifteen (15) flammability tests were performed for each value of packing ratio in the case of variable thickness (three (3) tests in the case of constant thickness). At ADAI/Coimbra, eight tests with varying thicknesses were carried out for each case.

3.3 Samples Preparation

At ADAI/Coimbra University, dead *Pp* and *Ws* fuels were dried and ignited, whereas, at LEPM/USTO-MB, live *Ph* needles were collected, dried, and ignited on the same day. Although moist fuels might be considered, for the sake of simplicity, we limited ourselves to dried fuels, and all fuels (dead and alive) were completely dried. A microwave oven with a power of 800 W and a drying period of 3 minutes was employed [15]. During this drying time, the fuel reached a minimal mass without changing color. Microwave ovens achieve comparable drying results to conventional methods [15, 16], but with substantially shorter drying times and less loss of volatile organic components. This guarantees that fuel drying and igniting tests are completed promptly, preserving the live property of the fuels (*Ph* needles).

Needles were packaged and placed in a cylindrical wire-mesh basket with a 10 cm diameter with around 51% porosity (see Fig. 3). The ADAI/Coimbra University sample holders (see Fig. 3b and c) had the same geometry and size as the LEPM/USTO-MB sample holders (Fig. 3a) but with fewer holes at their borders (with about 5% porosity). The porosity of the sample was found to influence ignition time. The sample holder holes and the porosity of the fuel bed may contribute to the overall sample porosity. However, Bartoli et al. demonstrated that the porosity of the holder did not affect ignition time under natural air flow conditions [10], which is the case of the present study. Furthermore, because the same sample holder was used in the current study for each fuel type with a natural flow, ignition time is expected to be influenced only by fuel bed porosity. The fuel bed thickness (e_{fb}) was measured with a graduated ruler with a resolution of 1 mm. Although, in real litters, the fuels are organized randomly, samples were produced with caution to maintain identical species fuel particle arrangements (parallel) as much as feasible to reduce local porosity dispersion and hence ignition time fluctuations. This homogeneous organization of the fuel



Fig. 3 Different types of fuels in sample holders: **a** *Ph* needles, **b** *Pp* needles, **c** *Ws* particles

Table 1 The physical properties of the species used in this work

Species	Ph [21]	Ph [23]	Pp [22]	Ws [24]	Ws [24, 25]
ρ_p (kg/m^3)	789	716 ± 96	555	268	285 ± 25
SVR (m^{-1})	7377	7440 ± 360	5115	/	2342

bed may under-estimate radiation heat transfer and radiation penetration through the sample (due to shadow effects) [17–19] compared to real beds. However, the present work aims to determine, as accurately as possible, the trend of ignition time as the compactness is varied so that any eventual non-monotonic behavior can be clearly distinguished from either a plateau or monotonic trend. This trend distinction requires minimizing ignition time standard deviation.

The apparent density of the fuel bed ρ_{fb} of the same cylindrical geometry as the holder (of diameter D), can be calculate using Eq. (2):

$$\rho_{fb} = \frac{m}{Se_{fb}} = \frac{4m}{\pi D^2 e_{fb}} \quad (2)$$

Here $S = \pi D^2/4$ is the fuel bed area. For convenience, instead of apparent density, one can use the packing ratio ϕ , defined in the introduction (Eq. 1), $\phi = \rho_{fb}/\rho_p$. The porosity (the proportion of air volume in the fuel bed) is hence directly related to the packing ratio as $1 - \phi$. The packing ratio is adjusted by modifying the fuel bed mass, m , and/or its thickness e_{fb} , with the surface S remaining constant and corresponds to the base of the cylindrical holder. When the fuel bed thickness e_{fb} remains constant, the packing ratio is proportional to the fuel load $m'' = m/S$ from (1) and (2). The surface-to-volume ratio SVR was also found to affect the ignition and combustion parameters of the fuel bed [9, 20]. Table 1 shows the average particle properties (density ρ_p , and SVR) for the studied fuels [21–25]: from literature [21, 22, 24] and determined by direct dimensional analysis of fuel particles [23, 25]. The values from literature are considered, since they are within the errors of the direct measurement method. The detailed fuel bed test conditions are presented in Table 2 (Appendix A).

The density of the *Pinus Pinaster* needles varies widely between 500 to 600 (kg/m^3), and even 927 kg/m^3 [21]. The value used to calculate the packing ratio in this paper is that measured at the same location of the experiments, with a density around 555 (kg/m^3) and a surface to volume ratio around 5115 (m^{-1}) [22].

The physical parameters of the porous fuel beds influence radiation transmission and absorption. The mean free path of radiation is defined by Eq. (3) [26]:

$$\delta = \frac{4}{\phi \times SVR} \quad (3)$$

In this context, the SVR of the fuel bed is defined as the average surface-to-volume ratio of the individual fuel particles, a common simplification that characterizes the fuel bed's fineness [5, 27]. This value was determined for each fuel type as described in Table 1. For isotropic fuel beds, a correction factor is sometimes applied to Eq. (3) to account for shadow effects [17–19]. However, since the primary aim of this work is to identify the general trend of ignition time (i.e., whether it is monotonic or exhibits a minimum) rather than to predict its absolute value, the uncorrected form of the mean free path is used for all analyses. We acknowledge that this introduces a systematic overestimation of δ , but it does not affect the identification of the overall trend.

4 Results and Discussion

4.1 Ignitability and Combustibility

The effect of compactness on ignitability and combustibility is now examined. Ignitability is assessed by the ignition time. In a standard cone calorimeter, combustibility is best described by the heat release rate (HRR) and the effective heat of combustion (EHC), derived from oxygen consumption measurements [28]. However, the present experimental setup, while using a cone calorimeter as a radiant heat source, is not equipped with an oxygen consumption calorimetry system. Therefore, HRR and EHC cannot be quantified. Instead, combustibility is assessed through the mass loss rate (MLR) and the flaming duration. These parameters provide a robust qualitative and comparative measure of combustion intensity and persistence for the same fuel type under different compaction levels, which is the primary focus of this study. It is worth noting that from the proportionality relationship $HRR = EHC \times MLR$ [28], the MLR and HRR have similar evolution trends for the same fuel.

Now let us start with ignitability, where ignition time of live dried fuels (*Ph* needles) with two different compacting conditions are compared to two dead fuels (*Pp* needles and *Ws* sticks). Dried live *Ph* needles are known to have the highest flammability due to resin content and fine fuel structure, while dead *Pp* needles have slightly lower flammability. Finally, dead *Ws* sticks are fast burning but less intense due to their low lignin and resin content [29].

Figure 4 shows the effect of compactness on ignition time for these fuel and compacting conditions. In this figure, standard deviations of ignition times are presented for all the considered fuels contrary to the previous studies where only average values were presented [5–7]. These results are also presented in Table 3 (see Appendix B) by keeping the packing ratios with variable thickness as close as possible from those with constant thickness. If the strength of ignition time is examined, ignition time seems comparable within errors between constant and variable thickness conditions for *Ph* needles (Fig. 4a and b), except at high compactness ($\phi \sim 40\%$), where fuel beds with constant thickness ignite faster (See

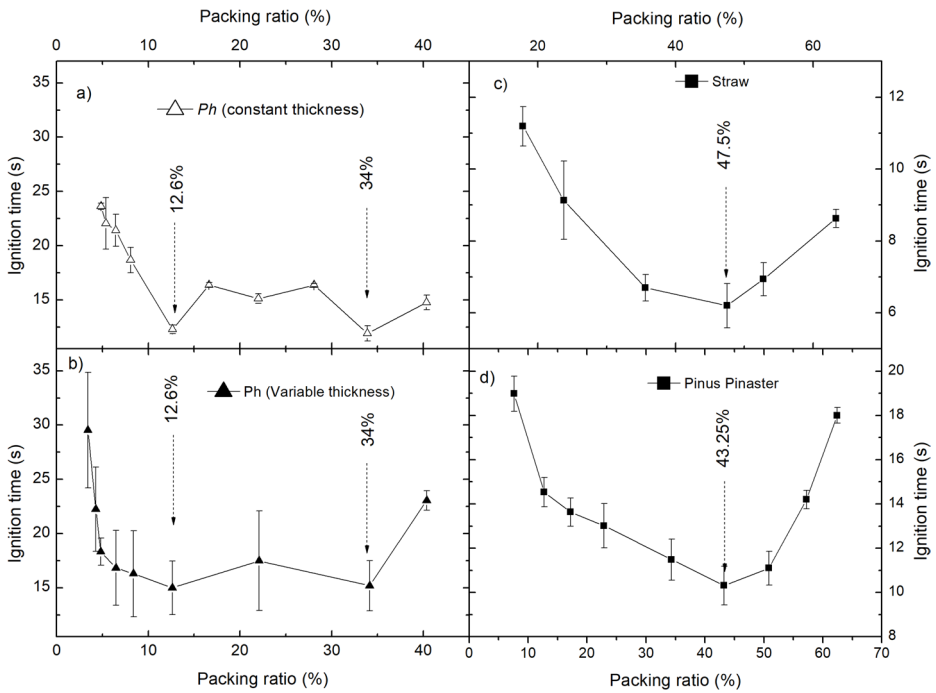


Fig. 4 Average ignition time vs. packing ratio for (a) *Ph* with e_{fb} constant, b *Ph* with e_{fb} variable, c straw, and d *Pp*

Appendix A). Ignition time for *Ph* needles is also comparable to that of *Pp* needles, but *Ws* sticks have a shorter ignition as expected [29]. The trends observed in Fig. 4a and b for *Ph* needles and in Fig. 4c and d can be analyzed in two ways:

- Considering only the average values and ignoring the error bars: the non-monotonicity observed previously is confirmed, where at least one minimum ignition time is observed for all the fuels considered. In particular, two minima are seen for *Ph* needles at packing ratios of $\phi = 12.6\%$ and 34% . The same optimum ratios (ratios with minimum ignition time) are obtained whether in the case of constant (Fig. 4a) or varying thickness (Fig. 4b). The increase in ignition time may be attributed to the increase of thermal inertia and decreased net heat flux (absorbed) at the surface. Samples with a very high packing ratio have a high thermal inertia but absorb nearly all incoming radiation at the surface (little or no in-depth radiation). Specimens with a very low packing ratio have low thermal inertia but have significant in-depth radiation heat transfer. Using this concept, the optimum (minimum ignition time) may be attributed to a competition between increasing thermal inertia and decreasing in-depth radiation. The other cause of the optimum may be attributed to the transition to optically thick fuel bed because of further decreasing in-depth radiation (Appendix A). The other fuels exhibit one minimum ignition time at $\phi = 47.5\%$ for Straw fuels (Fig. 4c) and $\phi = 43.25\%$ for *Pp* fuels (Fig. 4d). The increase in ignition time beyond the optimum is less pronounced for straw, possibly because its structure allows better airflow even at higher compactness,

mitigating some of the delays seen in denser pine fuels.

- *Considering both standard deviations (error bars) and average values:* In addition to the use of standard deviations, the significance of differences in mean ignition time between different experimental conditions was assessed using two-tailed, unpaired Student's t-tests. A p-value of less than 0.05 was considered indicative of a statistically significant difference. This analysis was applied to determine if the apparent minima in the ignition time versus the packing ratio (for constant, and variable thickness) plots represented significant departures from their neighboring data points :
 - In the case of constant thickness (Fig. 4a), both minimum ignition times at 12.6% and 34% are well separated from adjacent points within errors (from 0.1s to 0.7s) confirming the minima at 12.6% and 34%. Statistical analysis confirmed that the differences between these minima and their adjacent data points were statistically significant ($p \ll 0.05$), confirming a double optimum trend. Recall that in this case the optimum ratios correspond to optimum loads (the thickness being constant).
 - Regarding the case of variable thickness (Fig. 4b), a similar non-monotonic trend was observed for Ph needles but the two minima are less pronounced, and overlap with the nearest points (the errors may reach 5s) probably due to the packing ratio estimation errors. The relative errors of the measured mass and thickness are much larger in this case especially for small thickness (see Table 2 in appendix A). T-test analysis showed that the difference at the second minimum was statistically significant ($p < 0.05$). The difference at the first minimum was marginally non-significant ($p \sim 0.054$) but, when viewed in the context of the entire dataset and the significant second minimum, supports the conclusion of an overall non-monotonic relationship despite the errors. Hence, this trend is not an artifact of noise, but is a real phenomenon tied to radiation absorption and thermal inertia.

Regarding the other fuels (Straw and *Pp* needles), the optimum ratios are well distinct from adjacent points, and t-test analysis confirms the statistical significance between the ratios at minimum ignition and their neighbors. The trends observed in Fig. 4 are not affected by the openings of the holder, since the same holder is used for all considered compactnesses. Even if these openings influence ignition time, the added porosity should only translate these trends.

Note here the large observed dispersion of the optimum ratios, ranging from 12 % for *Ph* needles (Fig. 4a and b) to 47.5 % for *Ws* (Fig. 4c). This may be caused by the different types (resin and cellulosic composition and density) and shapes (SVR) of the considered fuels (See Table 1). The SVR, which contributes significantly to the volatile's emission during ignition, appears in the expression of the mean free path in Eq. (3), but not in that of the packing ratio. If the variation of the mean free path is considered instead of the packing ratio, the large dispersion of optimum ratios observed in Fig. 4 is significantly narrowed, in Fig. 5, to a small range of mean free path of only 2.8 mm width, centered at around $\delta = 3$ mm. The value of $\delta = 3$ mm was found to correspond to the transition from optically thin to optically thick regime [7]. The above discussed correction to Eq. (3) due to the homogeneous arrangement of fuel particles may only shift the mean free path in Fig. 5. As a result, the mean free path (δ) emerges as a more universal parameter than the packing ratio alone. Radiation absorption, controlled by δ should be among the main parameters contrib-

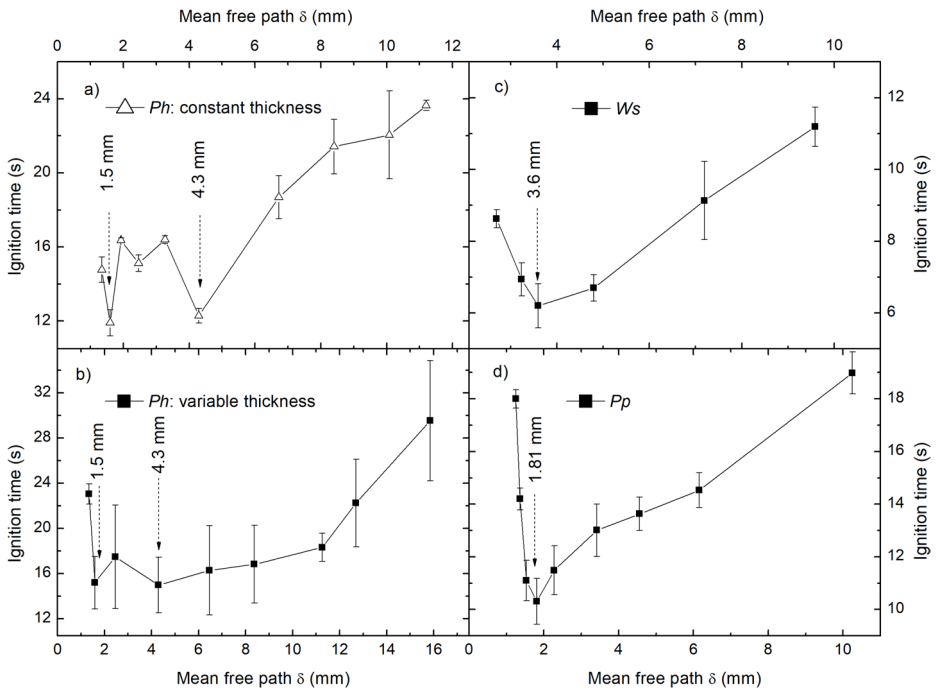


Fig. 5 The same results as in Fig. 4 but presented in terms of the mean free path of radiations

uting to the minimum ignition times observed in these figures, although cooling convection may contribute to the overall heat transfer for porous fuel beds. Further research is critical to map ignition behavior across all wildland fuel scenarios.

These new optimum ratios observed for broader range of packing ratios reveal more complex dynamics. From a practical point of view, these results suggest that moderate compactness (e.g., 10–35% for needles) may pose higher ignition risk (shorted ignition time). Very loose or very dense fuels could be less prone to ignition under similar heat fluxes.

While the non-monotonic trend is likely to persist for similar fuels near the studied range of packing ratios, extrapolating to extreme ϕ values or dissimilar fuels requires caution. It is expected for extremely low packing ratios ($\phi \ll 3\%$), that ignition times could be even longer due to insufficient fuel continuity or excessive heat loss to air gaps. For example, in sparse fuels (e.g., scattered litter), ignition might be unpredictable or delayed, aligning with probabilistic ignition behavior noted in prior work [4]. For near-solid fuels ($\phi \rightarrow 100\%$), ignition could resemble homogeneous materials, where surface heating dominates and in-depth effects vanish. For example, densely packed mulch or compacted biomass might exhibit slower ignition due to limited oxygen diffusion and deeper heat absorption.

Now let us examine the effect of compactness on the fuels combustibility described by the flaming duration. As discussed above, a shorter flaming duration is observed for straw sticks, while for compact fuel beds (in case of constant thickness), the flaming duration significantly larger. This is due to high fuel mass and the small in-dept radiation. In contrast to the trend observed for ignition time in Figs. 4 and 5, the effect of compactness on flaming duration shows a monotonic variation within the whole range of packing ratio Fig. 6a

(or mean free path Fig. 6b). In these figures, the flaming duration is nearly constant for low packing ratio (large mean free path) and increase the ratio is increased (as the mean free path is decreased). The Y-axis has a logarithmic scale to allow a rough estimate of the threshold ratio (mean free path) separating the constant from the increasing trend. The threshold ratio depends on the kind of fuel:

- 12.6% for *Ph* needles with variable thickness,
- 34% for *Ph* needles with constant thickness,
- 43% for *Pp* needles,
- 47% for *Ws* sticks

The monotonic increase in the flaming duration shown in Fig. 6a has been attributed to the reduction of airflow inside the fuel bed because of the increase in compactness [29, 30], which leads to a decrease in the rate of combustion. It is convenient to describe this behavior by varying the mean free path δ instead of the packing ratio. For very small values of δ (compared to the threshold value), only a thin top surface of the fuel bed (corresponding to δ) is heated by radiation, and then ignited. After ignition the remaining part (nearly the whole bed) contributes to flaming combustion. The flaming duration is then proportional to the mass of the fuel bed. As the mean free path is increased, a thicker layer of the bed contributes to ignition, while the remaining part concerned by flaming combustion decreases. As the mean free path becomes comparable to the fuel bed thickness ($\delta \sim e_{fb}$) the whole

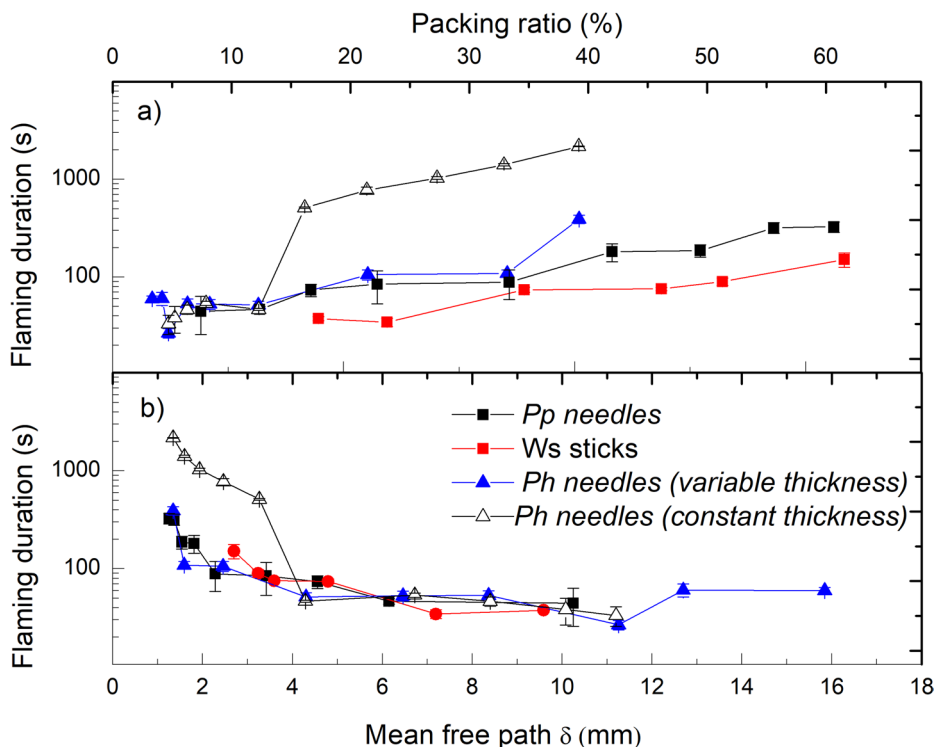


Fig. 6 The average flaming duration in a logarithmic scal vs. **a** packing ratio, **b** mean free path

sample is heated and ignited, leading to a minimum flaming duration (threshold mean free path). A further increase in the mean free path will not change the flaming duration, which is the burning time of the whole flaming sample. This effect is more pronounced when the sample thickness is maintained constant. In this case, the packing ratio is proportional to the mass of the sample. As observed for the optimum ignition, the transition from the decrease to the constant behavior of the flaming duration seems to occur at a significantly reduced range of mean free path thresholds δ between 3 and 4 mm. This interval corresponds roughly to the transition from optically thin to optically thick regimes of the fuel bed. This reveals that, for such a scenario of primarily radiative heating, radiation absorption should be one of the key parameters influencing flaming duration as well as ignition process.

To understand the monotonic behavior of the flaming duration, it is important to distinguish organic volatile components from the heavier components. As described by Hamamousse et al. [15], the ignition process is mainly involved by the volatile (light) components, while heavier components are only dissociated and consumed during flaming. For small values of the packing ratio (i.e. large porosity/mean free path), the enhanced radiation penetration leads to the flaming of the whole fuel bed, evaporating thus all its volatile components. The remaining heavy components do not depend on porosity but on the fuel mass, which varies only slightly for large porosity. This leads to a slightly varying flaming duration. For large values of the packing ratio (small porosity/mean free path), only the top thin layer, corresponding to the mean free path of the fuel bed, is involved by ignition, and the flame appears at its surface. The heat released by this flaming layer is thus transferred to the nearest inner layers, leading to its ignition and consumption, and so on. In the case of constant thickness (open triangles), this may lead to a dramatic increase in the flaming duration as fuel mass increases.

In summary, the packing ratio is the relevant parameter to simulate ignition time, and the rate of spread rather than considering the fuel load alone, used in most fire spread simulation models [31–33]. Some simulations use fuel models, which provide a rough indication of the fuel heights.

4.2 Mass Loss and Mass Loss Rate

The mass loss and mass loss rate results are presented in this section only for *Pinus halepensis* needles at different compactness ($\phi \leq 22\%$) and in cases of varying thickness. As combustion process represented by the flaming duration, showed a monotonic behavior, this study is restricted to a small range of compactness including the first optimum ignition.

Figure 7 shows the time evolution of the normalized mass of the fuel bed, from its exposition to the cone calorimeter (at time 0s) through its ignition and combustion processes until extinction. Samples at three different compactness (6.4%, 12.6% representing the first optimum ignition, and 22%) were considered. The corresponding initial mass values m_0 are respectively 4.8 g, 4.7 g, and 8.2 g (see appendix A). The mass loss curves show similar decreasing trends for all the cases of compactness. Once the fuel is subjected to an external heat flux (at time $t=0$ s), the mass loss evolves according to the following steps:

- The sample temperature increases, and the mass loss decreases linearly due to volatiles emission (dry samples) until ignition is reached.
- For the highest packing ratio (22%), a smooth non-linear decrease follows the step of

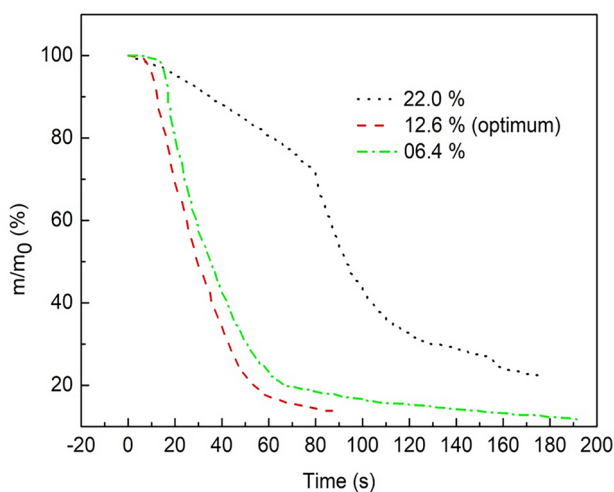


Fig. 7 Time evolution curves of the normalized mass for *Ph* needles for the following values of compactness/initial mass: $\phi/m_0 = 22\%/8.2g$, $12.6\%/4.7g$ (optimum ignition), and $6.4\%/4.8g$

linear trend (after 18s exposition, see appendix B). After the appearance of a single flame at ignition, it spreads (during of around 60s) towards the fully developed flame, where the whole sample surface is flaming, as discussed above. This step is not observed for low compactness (Fig. 7), due to the quick spreading (1–2 s).

- The fully developed flame is reached at the growth time (see above), and is followed by a step of sharper mass decrease (MLR increase), with a large release rate of combustion products.
- This step ends at the flame extinction. Here, a larger amount of unburnt fuel remains for $\phi = 22\%$ (around 20%) compared to the cases of low compactness (around 5% with mainly char oxydation). This difference may be due to the non-combustion of the inner layers and the remaining smouldering combustion after flame extinction.

To explain the effect of compactness on the sample mass dynamics, let us examine the behavior of the mass loss rate (MLR) during the ignition/combustion processes. The MLR corresponds to a derivative of the mass loss, estimated from the smallest time interval between successive values of the recorded sample mass (i.e. $1/3$ s). According to Lyon et al. [5], when the surface temperature reaches the pyrolysis temperature ignition occurs, then the mass-loss rate (MLR) increases towards a critical (maximum) value. Figure 8 shows the mass loss (and MLR) evolution for low (6.4%) and high (22%) compactness.

For the low compactness, the sharp decrease in the mass appearing in Fig. 7 just after ignition corresponds to a sharp increase in MLR towards its maximum value (see Fig. 8a). Here, the transition from the single flame appearance at ignition to the fully developed flame covering the entire fuel bed is as quick as it does not appear (as discussed in Fig. 7), and the growth time (i.e., fully developed flame) is confused with ignition time in the scale of this figure. The MLR increases abruptly towards its maximum value of about 60 mg/s. This is due to the ease of radiation penetration throughout the whole fuel bed, leading to a

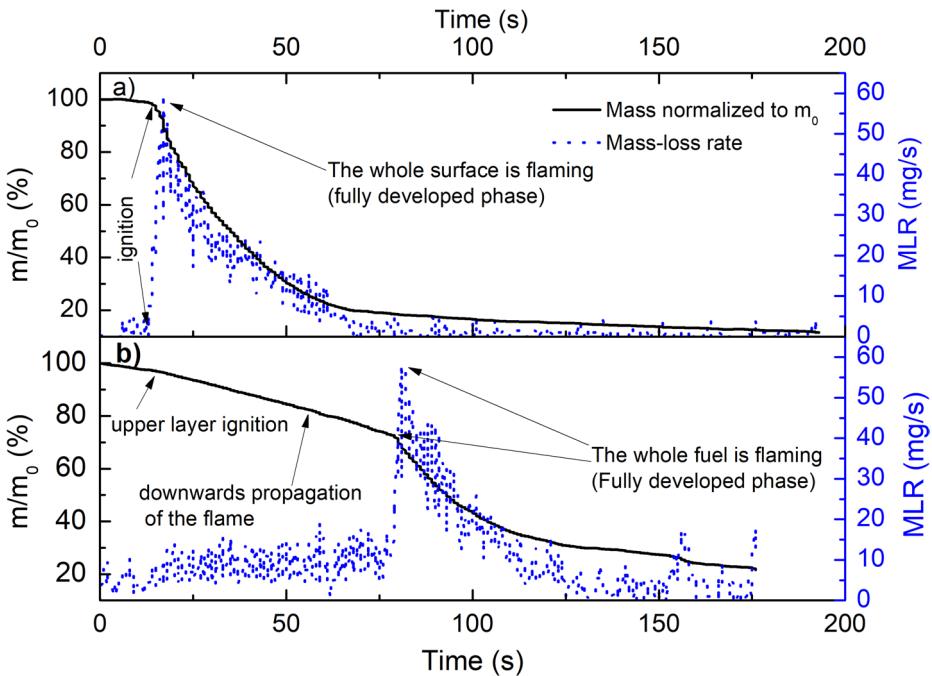


Fig. 8 Evolution curves of normalized mass and mass-loss rate (MLR) for *Ph* needles for (a) $\phi = 6\%$ and (b) 22%

rapid increase in temperature and a quick release of flammable gases. Beyond the maximum MLR, a slow decay phase occurs until extinction.

As the fuel bed is further compacted (22%), the growth time, which marks the sharp decrease of mass loss (fully developed flames) is significantly shifted by around 60s from ignition time as discussed above (Fig. 7), where the flame spreads only slowly within a thin layer at the sample surface, with MLR fluctuations of $\sim 10\text{mg/s}$ (see Fig. 8b). The sharp mass loss decrease/MLR increase at the growth time is slower than for low compactness.

During this step, the flames spread vertically within the bulk towards the inner layers of the fuel bed, until the MLR reaches its maximum value of around 60mg/s after around 20s of vertical spreading (compared to the instantaneous increase of 1 to 2s for the porous fuel beds). Then a slow decay phase occurs until flame extinction. After extinction, still large MLR fluctuations ($\sim 10\text{mg/s}$) occur compared to lower compactness, probably due to the persistence of smouldering combustion.

Now let us analyze the influence of packing ratio on the shape of MLR, which shows time evolution of the MLR for three different values of compactness. In Fig. 9, the shape of MLR is analyzed through the three parameters already defined in Fig. 1: the peak MLR, the upper width, defined as the Full Width at Half Maximum (FWHM, σ), and the lower width, defined as the duration (x_t) between the flame extinction time and the growth time.

- The peak MLR seems independent or only slightly varying with compactness (around 60mg/s). This agrees with the results of El Houssami et al. [7] for *Pitch pine* needles

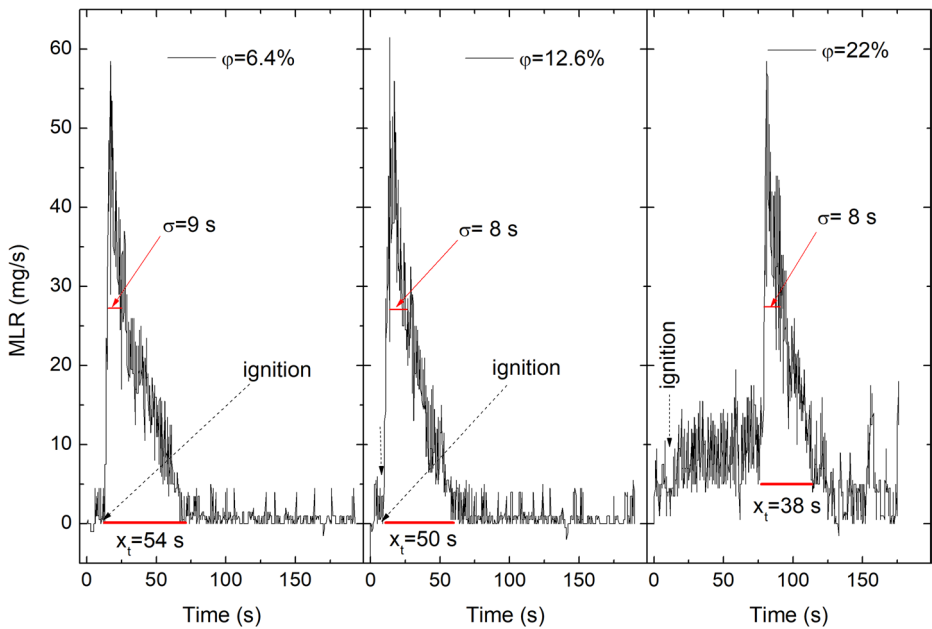


Fig. 9 The MLR evolution of *Ph* needles for: **a** $\phi = 6.4\%$, **b** $\phi = 12.6\%$, and **c** $\phi = 22\%$

although the applied heat flux was much larger.

- The upper width: The FWHM seems to be insensivity to compactness within statistical errors for the considered cases (approximately $\sigma = 8 \pm 2$ s). This does not agree with the findings of El Houssami et al. who found that the width of the peak MLR was affected by the fuel bed density ρ_{fb} (see Fig. 8 of [7]). However, the maximum considered fuel bed density was 40 kg/m^3 corresponds (from Eq. 2) to a packing ratio of around 6.6%, by using the *Pitch pine* particle density (given in Table 1 of [7]), corresponding here to our lower compactness 6.4 %. If one considers both present results and those of [7], the upper width σ should saturates for the packing ratios considered here. Further investigations at very low and very high compactness are necessary to confirm this trend.
- The lower width (x_t): This parameter defined in Fig. 1, seems to insensivity to compactness, within errors, for low values of the packing ratio, $x_t = 51 \pm 3$ (s). Whereas, for high compactness ($\phi = 22\%$) this width decreases significantly ($x_t = 39 \pm 2$ s, for $\phi = 22\%$). However, the period of flame spreading before the sharp increase of MLR phase is large (~ 60 s) making the total flaming duration larger (see Fig. 6a). Hence, there should be a competition effect between the flame spreading period and the lower width x_t . x_t is maximum when the spreading period is vanishingly short, but decreases when this period increases (slower flame spreading). Further investigations both on x_t and the flame spreading period are necessary to seek for the threshold packing ratio where the lower width starts decreasing, and its correlation with the optimum ignition.

5 Conclusion

The influence of compactness on the flammability (ignition time) and combustibility (flaming duration) of three different wildland fuels (live dried *Pinus halepensis* needles, and dead *Pinus Pinaster* needles and *Wheat straw* sticks) was investigated experimentally using a small scale cone calorimeter. A wide range of packing ratios was investigated in this study (3% to 50%), by using two different conditions of compactness: by varying only the mass for a fuel bed thickness of 3 cm, and by varying both thickness and the mass of the fuel bed.

For each selected fuel, at least one minimum ignition was observed. In particular, two minimum ignition times were observed for *Pinus halepensis* at packing ratios of about 12.6% and 34%, both in case of varying or constant the thickness, while the minimum ignition time was observed at 43.25% and 47.5% respectively for *Pinus Pinaster* and *Weat Straw*. If the mean free path is considered as a control parameter instead of packing ratio, the range of mean free parth with minimum ignition time is significantly reduced to a few millimeters. This indicates the important role of radiation in the heating and flammability process for this scenario of primarily radiative heating.

When examining the flaming duration, which represents the flaming combustion, a monotonic behavior was observed with a nearly constant flaming duration for sufficiently low compactness, and a significant increase when the fuel bed is much more packed. A threshold packing ratio was found to separate the two trends, and corresponds to a transition from optically thin to optically thick regimes. This optical transition may explain the optimum ignition at 34%.

The mass loss and mass loss rate were found to be sensitive to the packing ratio with similar trends. The mass decreases linearly until ignition (constant mass loss rate). Then it is the flame becomes instantly fully developed for low compactness, but for high compactness (22%) it spreads very slowly delaying the full development of the flame by around 60s. At the growth time (when the flame is fully developed), a sharp decrease in mass occurred, corresponding to an abrupt increase in the MLR until reaching the maximum value before decreasing slowly to flamout. The sensitivity to the compactness of the shape of MLR was also examined the maximum MLR, its full width at half maximum, and the delay between the growth time and the flamout. The two first parameters were found roughly insensitive to compactness, while the third parameter is reduced as compactness increases. The flame spreading period before the growth time has certainly a significant effect on this reduction. It should be further investigated and correlated to the observed optimum ratios for ignition.

The observed influence of compactness on both flaming ignition and combustion can be summarized as follows:

- The packing ratio is the relevant parameter for ignition instead of the load. The fuelbed thickness should not be ignored in fire spread simulation, where only the load is often considered.
- Fire risk is maximum for moderately compacted fuel beds compared to loose or dense fuels.
- Further increasing a the range of compactness beyond the present range is necessary to seek for more ignition complexities.
- Although the present study of the fuel bed combustibility by using the flaming duration and the mass loss rate, revealed interesting phenomena, like the slow flaming spread at

high compactness, but investigations using the heat release rate should be considered in future works to estimated the effective heat of combustion and to compare it to the gross calorific value of the fuel.

- An extensive characterization of the effect of compactness using higher incident flux is also necessary to examine the effect of the flux on ignition and combustion.

These will be the subject of forthcoming works.

Appendix A

Fuel Bed Test Conditions

See Table 2.

Table 2 Fuel beds characteristic

Fuel types	Variable thickness				Constant thickness			
	<i>Mass (g)</i>	<i>e (mm)</i>	<i>ϕ (%)</i>	<i>δ (mm)</i>	<i>Mass (g)</i>	<i>e (mm)</i>	<i>ϕ (%)</i>	<i>δ (mm)</i>
<i>Ph needles</i>	5.3	25	3.4	15.9	10.0	30	4.9	11.2
	5.3	20	4.3	12.7	9.0	30	5.4	10.1
	2.7	9	4.8	11.3	12.0	30	6.5	8.4
	4.8	12	6.4	8.4	15.0	30	8.1	6.7
	4.7	9	8.4	6.7	23.5	30	12.6	4.3
	4.7	10	12.6	4.3	30.9	30	16.6	3.3
	8.2	6	22.0	2.6	40.9	30	22.0	2.5
	21.2	10	34.0	1.6	52.2	30	28.1	1.9
	40.0	16	40.4	1.3	63.0	30	33.9	1.6
					75.0	30	40.3	1.3
<i>PP needles</i>	3.0	9	7.68	10.26				
	5.0	9	12.69	6.13				
	9.0	12	17.20	4.58				
	9.0	9	22.88	3.42				
	9.0	6	34.4	2.26				
	17.0	9	43.25	1.81				
	20.0	9	50.1	1.55				
	25.0	10	57.28	1.35				
	30.0	11	62.63	1.23				
<i>Straw</i>	4.5	12	21.7	9.6				
	4.5	9	28.9	7.2				
	9.0	12	43.4	4.8				
	9.0	9	57.9	3.6				
	10.0	9	64.3	3.2				
	20.0	15	77.2	2.7				

Appendix B

Ignition Tests Results

See Table 3.

Table 3 Ignition tests results of Fig. 4a

Fuel types	Variable thickness		Constant thickness	
<i>Ph needles</i>	ϕ (%)	t_{ign} (s)	ϕ (%)	t_{ign} (s)
	3.4	29.5±5	4.9	23.6±0.3
	4.3	22.3±4	5.4	22±2
	4.8	18.3±1	6.5	21.4±1
	6.5	16.8±3	8.1	18.7±1
	8.4	16.3±4	12.6	12.3±0.4
	12.6	15.0±2	16.6	16.4±0.2
	22.1	17.5±5	22.0	15.1±0.4
	34.1	15.2±2	28.1	16.4±0.1
	40.4	23.0±1	33.9	11.9±0.7
			40.3	14.8±0.7
<i>PP needles</i>	7.68	18.9±0.8		
	12.69	14.5±0.7		
	17.20	13.6±0.6		
	22.88	13.0±1		
	34.4	11.5±0.9		
	43.25	10.3±0.9		
	50.1	11.1±0.8		
	57.28	14.2±0.4		
	62.63	18.0±0.4		
<i>Straw</i>	21.7	11.2±0.5		
	28.9	9.1±1		
	43.4	6.7±0.4		
	57.9	6.2±0.6		
	64.3	6.9±0.5		
	77.2	8.6±0.3		

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Data Availability Data will be available on reasonable request.

Declarations

Conflict of interest The authors report there are no competing interests to declare

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