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Influence of fuel load on the flammability of live *Pinus Halepensis* needles

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Abstract

The fuel flammability, combustibility, and fire spread properties depend on several parameters, such as the heat flux, moisture content, wind, and the fuel load. Flammable ignition occurs when the emitted organic volatile components flow mixed with air reaches a minimum rate corresponding to the lower flammability limit. The gas flow of these components depends on the fuel quantity (load) and its temperature. Therefore, ignition time depends on the fuel load.

In this work, the effect of the load on ignition time of live *Pinus Halepensis* needles is investigated using a cone calorimeter (providing three incident heat flux intensities). The average fuel moisture content is around 50% on a wet basis. Ignition time exhibits an exponential trend for all the incident heat flux intensities considered with a correlation coefficient $R^2 > 0.96$. The exponent corresponds to a characteristic load $\bar{m}_0$ around 1 kg/m^2 slightly dependent on the incident flux within statistical errors. For very small loads compared to $\bar{m}_0$ ignition time is nearly independent of the load because the time required for water evaporation is neglected compared to that required for a volatile mixture with air to reach the lower flammability limit. For larger loads (in the range of 0.38 kg/m^2 to 1.27 kg/m^2), the time required for water evaporation introduces a shift in ignition time which increases linearly with the load. Finally, for large loads compared to $\bar{m}_0$, the fuel bed thickness becomes larger than the optical length, and only its top layer is heated, transmitting thus heat to the internal layers by conduction. Therefore, the internal layers evaporate water and cool the upper one, leading to the exponential ignition time with the load. For dry fuels, ignition time appears independent of the load.

1. Introduction

Fires are considered in ecology as one of the most important and traumatic disturbances. Mediterranean ecosystems are particularly sensitive to conditions favoring fires: repeated climatic droughts, strong and frequent winds, accumulation of combustible biomass resulting from forest plantations, the abundance of rural areas, and the low exploitation of the forest (Di Castri, 1981). During the period from 1985 to 2006, a total burned area of 779,872.11 ha was recorded for 32,354 fires. *Pinus Halepensis* and *Cork Oak* forests fuels paid the heaviest price. Based on these statistics, we choose to study *Pinus Halepensis* needles. Ignition conditions depend on several parameters such as the heat flux, water content, wind, load, etc. Regarding the first parameter, there is a critical heat flux for flammability (Terrah et al, 2018; Sabi et al, 2018; Mindykowski et al, 2008). Concerning the second parameter, it has recently been shown that there is no critical water content for flammability, but for each moisture, there is a sufficient heat flow to allow ignition (Terrah et al, 2018). During the exposition of the fuel to a heat source, its temperature rises, and flammable volatiles is emitted and mixed with air. The composition of gas in the air increases with temperature and reaches a critical concentration allowing ignition under a critical temperature. The time for gas flow to reach the critical composition (lower flammability limit depends also on the load). Ignition time dependence on the load is investigated here for different incident flux intensities.

2. Heat transfer and experimental setup

The *Pinus Halpensis* needles with an average moisture content of 50% (on a wet basis) are harvested the same day to ensure their live character. The sample is placed in a cylindrical holder with a diameter of $0.1\ m$, and exposed to thermal radiation flows ranging from 10 to $21\ kW/m^2$ provided by a cone calorimeter (Fig.1a) equipped with an electrical resistance of 3000W. The calibration of the heat flux is realized by using a heat flux sensor Hukseflux SBG01 working in the range from 0 to $200\ kW/m^2$. The desired heat flux intensities are obtained by varying the distance between the sample and the cone calorimeter (Fig.1b). Vegetation ignition is controlled by a pilot flame located 1cm above the sample. Ignition is considered successful if the flame persists for a time longer than 4s, and ignition time is recorded.

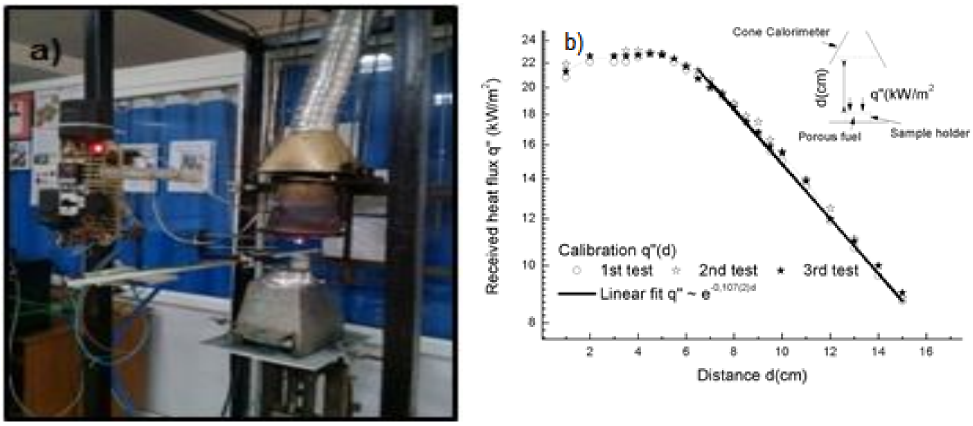

Figure1: a) the experimental setup, b) a schematic representation of the heat flux calibration

The net absorbed heat flux by the fuel $q"_{net}$ is related to the absorbed incident heat flux and that lost by the fuel bed. Neglecting conduction heat transfer, the net heat flux reads:

$$q"_{net} = aq"_{inc} - h(T - T_0) + \sigma\varepsilon\left(T^4 - {T_0}^4\right) \qquad (1)$$

Here h is the convection coefficient, σ is the Stefan Boltzmann constant, ε is the emissivity of the fuel, and T_0 the ambient temperature. The samples were prepared with caution to keep similar arrangements of the species as far as possible. As the fuel bed is porous, the heat transfer mechanism involves the packing ratio φ which measures the average volume proportion of fuel in the sample:

$$\varphi = \frac{4\,m}{S \times e \times \rho} \qquad (2)$$

Where m is the sample mass, S its surface, e its thickness, and $\boldsymbol{\rho}$ the particle density. The porosity (proportion of air in the bed) is directly related to the packing ratio $(1 - \varphi)$. The surface-to-volume ratio SVR was also found to influence the ignition and combustion properties of the fuel bed (Schemel et al, 2008; Santoni et al, 2014). Flammability properties might be influenced by the optical length δ of radiation that corresponds to the extinction coefficient defined as CFR (1981):

$$\frac{1}{\delta} = \frac{\varphi \times SVR}{4} \qquad (3)$$

This quantity is an important optical parameter of porous material, and allows the determination of the absorption probability a, which is related to the thickness e as Callister & Rethwisch (2914):

$$a\ \alpha\left(1 - e^{-e/\delta}\right) \qquad (4)$$

The replacing (2) in (3), this quantity is related to the fuel load ($\overline{m} = m/S$) as:

$$\frac{e}{\delta} = \overline{m}\,\frac{SVR}{\rho} \qquad (5)$$

Since the fuel considered is the same (same $\boldsymbol{SVR}$ and density), ignition time (t_{ign}) is related to the load $\overline{\boldsymbol{m}}$.

3. Results and discussion

Fig.2 shows the variations of ignition time with the load $\bar{m}$ for three heat flux intensities ($17\ kW/m^2$, $13.83\ kW/m^2$, and $10.93\ kW/m^2$). The load is changed by varying the mass of the fuel bed, the area S of the sample holder being constant. Note here that the depth of the fuel bed may change from one sample to another depending on the packing ratio from equation (2). From (5) the fuel bed thickness (e) varies linearly with the optical length (δ) for the same load. From this figure (presented on the semi-logarithmic scale) ignition time seems to increase exponentially with the load for all the heat flux intensities considered with a correlation coefficient larger than 0.96 as:

$$\left(t_{ign} \propto e^{\bar{m}/\bar{m}_0}\right) \tag{6}$$

The growth exponents determined from the fitting slopes in Fig.2, correspond to characteristic loads $\bar{m}_0$. The exponential trend appearing in Fig.2 involves a characteristic quantity as in other fields (like the relaxation time in charge or discharge of a condenser). The characteristic load seems to depend only slightly on the incident heat flux: $\bar{m}_0 \approx 1.05 \pm 0.05\ kg/m^2$ for an incident heat flux of $17\ kW/m^2$, $0.99 \pm 0.03\ kg/m^2$ for $13.83\ kW/m^2$ and $1.14 \pm 0.02\ kg/m^2$ for $10.93\ kW/m^2$). For small loads ($\bar{m} \ll \bar{m}_0$) ignition time is nearly constant. Indeed, as the load is sufficiently small, the whole surface of the sample will be heated at the same time, and the time for water to be evaporated is neglected compared to that of volatiles and their mixture with air to reach the lower flammability limit. For loads in the range $0.38 < \bar{m} < 1.27\ kg/m^2$ (i.e close to $\bar{m}_0$) ignition time increases linearly with the load (the time of water evaporation induces a delay before ignition).

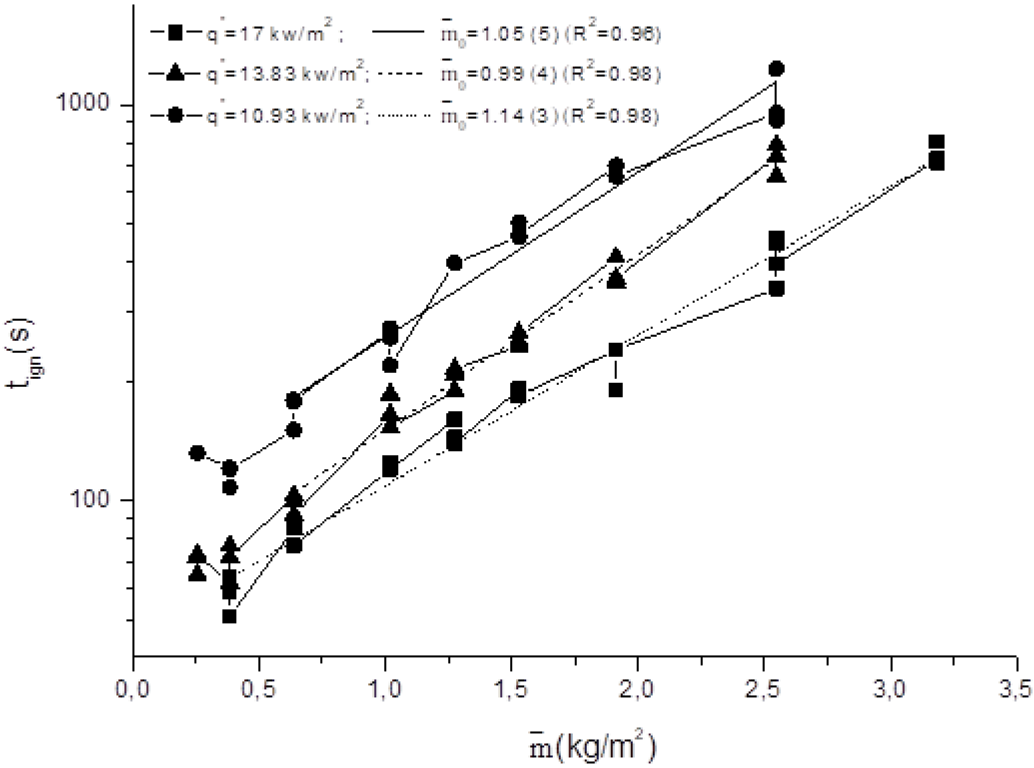

Figure2: Variation of ignition times vs. the load ($\bar{m}$) for the three different heat flux intensities: 17 kW/m², 13.83 kW/m² and 10,93 kW/m². The lines represent the exponential fits, and the characteristic loads are estimated from the fit slopes.

For larger loads ($\bar{m} > 1.27\ kg/m^2$) the trend of ignition time becomes exponential. The exponential trend is explained by the fact that the fuel bed thickness becomes much larger than the optical length, and the heat flow heats only the top layer of the fuel bed, which heats the internal layers by thermal conduction. The water evaporated from these inner layers cools the top layer which delays their ignition (Drysdale, 2011). This transition from a constant ignition time to an exponential increase with the fuel bed load can be explained by the transition from thermally thin to thermally thick fuel beds If the fuel bed itself is thermally thin, there is no temperature gradient, and all the water will be evaporated before ignition. If the fuel bed is thermally thick, there is a temperature gradient so the deeper layers of fuel could still be cool enough to be evaporating water (and diluting the pyrolyzed). Hence, the characteristic load ($\bar{m}_0$) corresponds to a crossover fuel bed thickness separating the thermally thin and thermally thick regions.

4. Conclusion

In this work, we studied experimentally the effect of the fuel load on ignition time using a cone calorimeter delivering three different heat flux intensities. An exponential trend of ignition time is observed for all heat fluxes, with the corresponding characteristic load of around 1 kg/m^2 slightly dependent on the heat flux. The exponential trend is explained for large loads ($\bar{m} > 1.27\ kg/m^2$) by a complex heat transfer process due to the large fuel bed, thickness compared to the optical length. Only a top layer of the sample is heated and heats the internal layers. Water evaporation of the inner layers cools the top layer and therefore delays ignition.

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