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The influence of packing ratio on forest fuel fire spread on a laboratory scale: no wind, no slope

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Abstract

The influence of Pinus Pinaster needles packing ratio on fire spread at laboratory scale is investigated experimentally and compared to other wildland fuels. The packing ratio was varied from up to 10% by changing the fuel bed load and thickness. An optimum ratio of 5.5% is obtained corresponding to a maximum rate of spread. This optimum ratio is close to that found by Rothermel for crib fuels. However, the rate of spread increases again for higher porosity, which suggests the existence of a second optimum ratio. Two optimum ratios were also observed by Rothermel for excelsior fuels and recently by He et al for experiments using laser-cut cardboard. Recently, two optimum ratios corresponding to a minimum ignition time were observed using Pinus Halepensis needles. The minimum ignition time for spreading fuels correspond to a maximum rate of spread. These ratios have been attributed to a maximum heat flux absorption by the fuel. The heat flux absorption effect on the rate of spread is discussed by using the fuel optical length. The obtained optimum ratio corresponds to a small optical length ($12\ mm$), which means that the heat flux is absorbed by the surface of the fuel bed. The second optimum ratio may correspond to an optical length much larger than the fuel bed thickness (around $50\ mm$). This corresponds to a bulk absorption of the heat flux. Further analyses of the mass-loss rate are provided to discuss thermochemical effects.

1. Introduction

Forest fire behavior is still far to be understood, due to the large variety of wildland fuels and their complex structure and composition. Burning conditions may vary significantly from one region to another because of the fuel spatial distribution induced by their moisture, density, surface-to-volume ratio, and packing ratio. The packing ratio has been found to influence directly the fire propagation (Z. Campbell-Lochrie et al, 2021), and the observed optimum ratio has been attributed to thermochemical effects (Rothermel, 1972). Further investigations suggest that the packing ratio directly affects radiative heat transfer to the fuel bed surface (Simeoni et al, 2011). A recent experimental study on a discrete fuel bed composed of laser-cut cardboards found that internal heat transfer affects the rate of spread (ROS) in the case of dense fuel (He et al, 2021). Heat transfer has been found recently to be the main cause of the non-monotonic behavior of ignition time as a function of packing ratio (Boutchiche et al, submitted). This work aims to highlight the relation between ROS behavior and absorbed heat flux at different packing ratios.

2. Experimental setup

Pinus Pinaster needles dried naturally with a moisture content of about 10% are used in this work. The vegetation is weighed and spread out on a square table of $0.8 \times 0.8\ m^2$ size that is placed on a digital balance A&D HW-100KGL with a resolution of $10\ g$ and a recording frequency of $1\ Hz$. The weight is recorded on a computer through a data acquisition software RSKey v.1.40 see Fig.1. To follow the variation of the height of the flame an optical video camera Sony FDR-AX53 and an infrared camera SC660 from FLIR were placed on the front of the table while a second optical video camera Sony HXR-NX30E was placed laterally to the table. The resulting videos were converted into images, and the flame height was manually measured against a vertical scale placed close to the sample.

Figure 1: The experimental setup at the Fire Laboratory of ADAI (Coimbra).

The samples are ignited at one side, and the variation with time of the front position was recorded to estimate the ROS. The fuel bed packing ratio $\boldsymbol{\varphi}$ is varied by varying its mass ($\boldsymbol{m}$) and height ($\boldsymbol{e_b}$) according to the following equation:

$$\boldsymbol{\varphi} = \frac{\boldsymbol{m}}{\boldsymbol{S}.\boldsymbol{e_b}.\boldsymbol{\rho}} \tag{1}$$

where $\boldsymbol{\rho}$ is the fuel particles density. The porosity measures the proportion of air in the fuel bed $\mathbf{1} - \boldsymbol{\varphi}$.

3. Results and discussion

The influence of compactness on rate of spread of the above described *Pinus Pinaster* is compared in Fig.2a to *excelsior* and ¼ inch *cribs* fuels (Rothermel, 1972) and laser-cut cardboards (He et al, 2021). The ROS behavior shows at least an optimum ratio for all presented fuels for $\varphi < 10$ %. An optimum ratio is observed for *Pinus Pinaster* (PP) needles around 5.5% close to that found by Rothermel for *cribs* fuels, but the ROS of PP needles increases again for smaller ratios as if they have another optimum packing ratio. Two optimum ratios have been observed also for excelsior fuels (Rothermel, 1972) and cardboards (He et al, 2021), and have been attributed to thermochemical effects. However, heat transfer has been found to be the main cause of non-monotonic ignition time (Boutchiche et al, submitted). As the ROS corresponds to the ignition time of the nearest fuels of the flame, absorption heat transfer might be also the cause of the optimum ratios observed for the rate of spread. Ignition and combustion are influenced also by surface-to-volume ratio SVR. The optical length of radiation heat transfer is related to these quantities by

$$\boldsymbol{\delta} = \frac{\mathbf{4}}{\boldsymbol{\varphi} \times \boldsymbol{SVR}} \tag{2}$$

In Fig.2b, the ROS is presented as a function of the optical length. The absorption probability decreases exponentially with with the fuel thickness ($e^{-e/\delta}$) (Boutchiche et al, submitted). As the optical length at the optimum ratio of PP needles is around $12\ mm$, much smaller than the fuel bed thickness which varies from $e =$ 40 to $e = 70\ mm$, the maximum ROS is characterized by a surface absorption of the heat flux similar to that of the *excelsior* fuel bed (around $20\ mm$) (Rothermel, 1972). As mentioned above, the ROS seems to increase again for larger lengths which corresponds to the existence of a second optimum ratio. This optimum ratio seems to corresponds to an optical length much larger than the fuel bed thickness, which means that the heat flux is absorbed by the whole fuel bed. A similar absorption behaviour occurs for *cribs* (Rothermel, 1972) and cardboards (He et al, 2021).

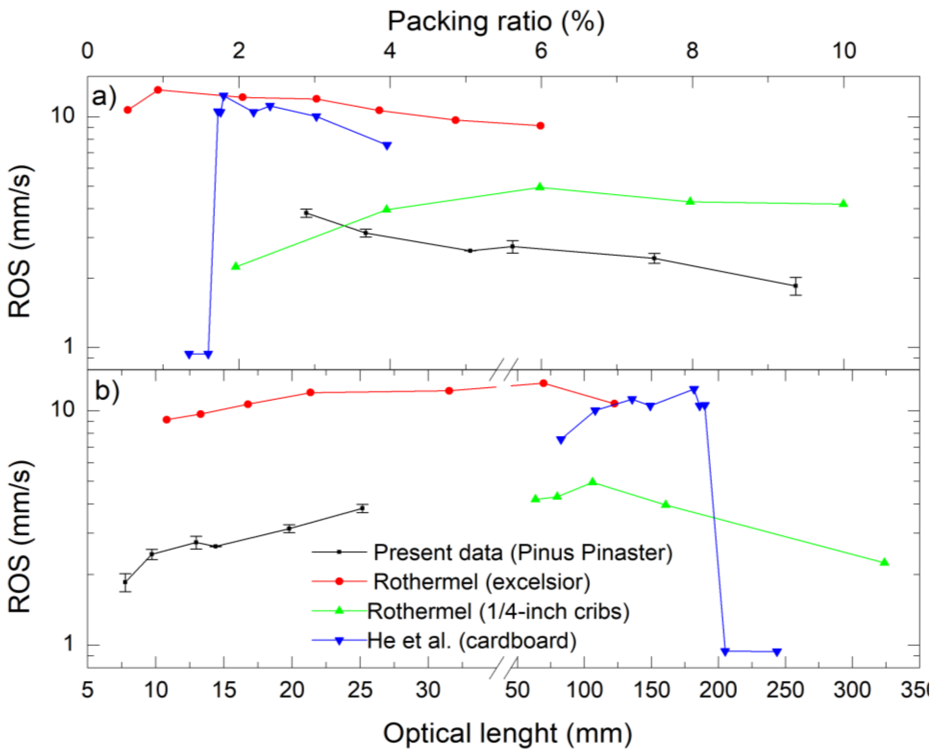

Figure 2: Rate of spread as a function of a) packing ratio, b) Optical length

Now let us examine the thermochemical effects through the mass-loss rate of the fuelbed during spread, which is proportional to the potential reaction velocity according to equation (35) of (Rothermel, 1972). Since internal combustion is involved during spread, the mass-loss rate corresponds to the emitted flammable gas, and is thus expected to vary with porosity. In Fig.3a the mass-loss rate evolution during fire spread is presented for an example configuration of fuel bed. Here, the contribution of glowing embers that remain in the burned area, and the pre-heating contribution of the foreward area are neglected compared to that of the burning area. After ignition, the burning rate seems to increase linearly with time during spread, and decreases when the forward front reaches the end of table. The increase of the burning rate may be explained by the increase of the burning area of the fuel as fire spreads. Indeed, at ignition, the front is a straight line, but becomes curved as the front advances due to the edge effects (see Fig.3b). At the edges, fire spreads slowly compared to the center because of the lack of nearest burning fuels contribution. Assuming the burning rate homogeneous, the increase of the curvature of the front during spread corresponds to an increase of the burning area, and thus to the increase of the total mass-loss rate. Therefore, the slope in Fig.3a may depend on the rate of spread. It is thus burning rate is the minimum for the initial line front,

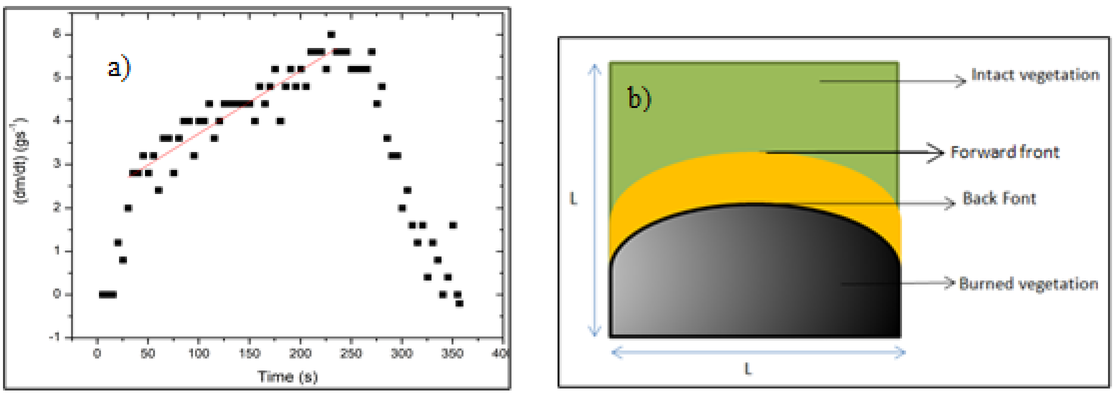

Figure 3: a) The mass-loss rate as a function of time of selected sample** $m = 1.2\ kg$; $e = 5.5\ cm$ **b) schematic view of the front during spread.

To examine the influence of the optimum packing ratio on potential reaction velocity, it is convenient to consider the minimum mass loss rate corresponding to the initial fire line. This avoids the contribution of the rate of spread on the burning rate. In Fig.4 the minimum mass-loss rate seems to be independent of the packing ratio within errors in the range of φ up to 10 %. Therefore, the optimum ratio observed for *Pinus Pinaster* in Fig.2 seems to not be caused by the burning rate (or reaction velocity (Rothermel, 1972)). The heat transfer mechanism may be the main cause of this non-monotonic behavior as found for ignition (Boutchiche et al, submitted).

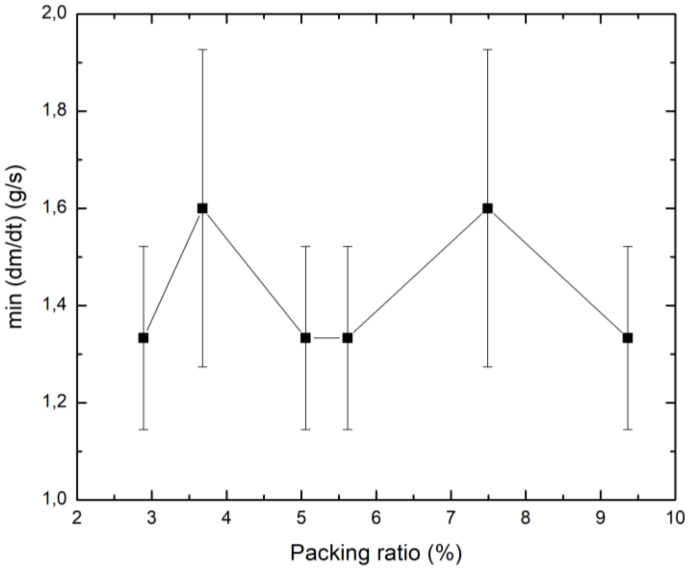

Figure 3: The mass-loss rate as a function of the packing ratio.

The flame height seems to follow the same trend as ignition time by varying the packing ratio. The flame heigh is not shown to avoid clutter.

4. Conclusion:

The effect of the packing ratio and optical length on the rate of spread of *Pinus Pinaster* fuels is examined and compared to those of other fuels in litterature. An optimum packing ratio corresponding to a maximum rate of spread is found for a ratio of 5.5 %, and the trend indicates the existence of another maximum rate of spread for a much smaller packing ratio. By using the optical length, the maximum rate of spread occurs at an optical length of about 12 mm much smaller than the fuel bed thickness, which corresponds to a maximum surface absorption. While the other maximum rate of spread is expected to occur at an optical length much larger than the fuel bed thickness, which means a bulk absorption of heat flux. Although an internal combustion occurs during spread, the mass loss rate seems to be independent of the packing ratio in the range of ratios considered.

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