An Experimental Study Evaluating the Burning Dynamics of Pitch Pine Needle Beds Using the FPA

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ABSTRACT

Pine needle litters, a key fuel in coniferous forest systems, are highly porous fuel beds. They provide a source of continuous fuel medium that can be easily ignited and will sustain flame spread on the ground during forest fires. This work represents an experimental study that is focused on the influence of the fuel moisture content on the burning dynamics and the flammability characteristics of forest fuel beds. The FM Global Fire Propagation Apparatus was utilized to obtain time to ignition, heat release rate, total heat released and CO/CO_2 concentration data. The methodologies applied in previous studies were improved with new modifications. The results were analyzed with respect to the sample's fuel moisture content as well as other test conditions, such as airflow condition (wind), sample holder openness and external heat flux. The importance of the fuel moisture content is critical to understand as the majority of fuels present in the natural environment have elevated moisture content compared to dead dry fuel. Samples studied are representative of wet ground fuels as well as live fuels which do burn when crowning conditions develop. The results presented here are a building block for developing an experimental database that can be used to understand the influence of environmental conditions on the flammability of porous forest fuels and assess the risks that comes with a wildfire. Furthermore, the data can also be used for fire behavior model validation.

KEYWORDS: Wildfires, flammability, calorimetry, forest fuels, Pitch pine, fuel moisture content, burning dynamics, Fire Propagation Apparatus

NOMENCLATURE LISTING

d	dead needles
FMC	total fuel moisture content on dry basis (24h conditioning)
HRR	heat release rate
LF	low flow (50 lpm, 6.7 cm/s)
l	live needles
lpm	liters per minute
m	mass (kg)
NF	no flow (0 lpm)
P.ri.	*Pinus rigida* (Pitch pine)
$\dot{q}''$	heat flux (kW/m^2)
SVR	surface area to volume ratio (m^{-1})
t	time (s)
THR	total heat(energy) released
V	Volume (m^3)
Greek	
α	volumetric ratio
ρ	density (kg/m^3)
Subscripts	
dry	dry mass of needles
gas	volumetric ratio of gas (porosity)
H_2O	water
initial	initial mass
moist	wet mass of needles
Superscripts	
()"	per unit area (m^{-2})
()*	bulk

INTRODUCTION

As wildfires continue to occur across the globe researchers are continuously working on understanding the burning behavior of these usually catastrophic fires. In the context of this study the environmental factors play a major part in the burning dynamics of vegetative fuels. It is the goal to assess the influence of these factors on laboratory scale samples. More specifically the focus of this study is the role of fuel moisture content on its ignition and burning behavior. In a forest fire the fuel is solid particles but as a bulk load it is not. One needle or one leaf is solid but a volume of these is not since it contains a substantial amount of air. This porosity makes vegetative fuels differ from usual solid fuels encountered in the built environment by a great extent since the value can be very high. The porous fuel packages, such as needle litter, a bush or a

crown of a tree that make up the fuel in a forest must be characterized in great detail before experimental tests can be evaluated.

Flammability characterization was described by Anderson as a combination of ignitability, sustainability and combustibility [1] and is widely used in past and present research. Works by various authors [1-7] focus on the flammability characterization of vegetation fuel, in various apparatuses. Samples used in these studies are single layer [2-4] or thicker fuel beds [5-7]. Various tests conditions such as airflow, bulk properties, fuel moisture content (FMC) were considered and the analysis focuses mainly on evaluating ignition delay time (also referred to as time to ignition), heat release rates and critical mass loss and ignition temperature data. Time to ignition is specifically an important parameter because flame spread can be described as a series of ignition of adjacent fuel particles [8]. The flame spread through porous vegetative fuel beds has been studied by many research groups [8-14] and it was determined that the major factors that influence the flame spread are wind, slope, FMC, as well as fuel loading and bulk properties of the fuel bed. One component of these works is the moisture of extinction, which is described as the FMC of a fuel above which a flame spread is not sustained [2, 8]. The moisture of extinction relates the flammability and flame spread research. It can be found experimentally as determined by Dimitrakopoulos in [2] and used in fire spread models as a damping coefficient as explained by Rothermel in [8]. It is not the objective of this study to determine the moisture of extinction but it shows that high fuel moisture content is needed to reduce the flammability properties of the samples tested. The work on flammability is related to the current work, presented here, as similar species and test conditions are evaluated. However the sample size, experimental procedures and analysis of the data widely differ from one another.

As Jervis et al. mentioned in[6], one can make an analogy to a fire in the realm of solid material in the built environment: when a new building is developed the fire protection system must be designed according to what material (as well as other factors) will be expected in the building. These materials (building material, interior finishes, etc.) undergo testing and flammability characterization. Now, in order to have an appropriate fire protection system a design fire must be chosen. This design fire will be chosen according to the flammability characteristics of the present materials. These materials must be tested before being allowed to be incorporated in a new building. If some material is unknown in the building the designer of the protection system cannot make an adequate selection for a design fire because the worst case scenario should be chosen and this particular unknown material might be the most flammable. This translates directly to wildfires. The fuel and its burning behavior must be known in order to understand what kind of fire can be expected in a certain ecosystem. As standardized laboratory experimentation is used in the flammability characterization for solid material it is reasonable to apply these to vegetative fuels. The difficulty to do so lays in the nature of the fuel packages which provide additional properties (bulk properties) that do not play major roles in solid material flammability. Several steps have been taken to accommodate the existing standard equipment to fit the needs in wildfire research, e.g. porous sample holders used by Schemel *et al*. [15].

As this is a continuation of previous flammability studies it is the intent to improve the experimental protocols with additional modifications. Simeoni *et al*. [16]summarized studies pertaining flammability and burning dynamics of forest fuel in great detail. The studies evaluated flammability parameters (time to ignition, heat release rates, and mass loss rates) with respect to various test condition such as sample basket openness, and airflow condition. From these results a simplified 1-D model was developed to simulate the ignition behavior of porous fuel samples. In [7] Bartoli *et al.* considered the main parameters influencing the combustion dynamics. Besides airflow and basket openness also species variation and sample loading variations were considered. Thomas *et al*. focused on the study of flammability of pine needle beds in [17] and [18] with respect to various test conditions, supplementing the results found by Simeoni and Bartoli by studying North American needle species. A very detailed ignition study was presented that evaluated the time to ignition for a wide range of heat flux conditions. Furthermore the FMC was introduced as an addition test parameter. Parallel to these works Jervis [6] evaluated the influence of fuel moisture content on the burning dynamics of pine needle sample. Even though, Jervis' and Thomas' works have similarities both are supplementary to the other. Differences can be found in the sample properties, experimental set ups and the bases of analysis.

PARTICLE AND BULK PROPERTIES

In order to clearly characterize the fuel (needles) and the sample, a set of particle and bulk properties must be obtained: (1) Particle density; (2) Surface area to volume ratio (SVR); (3) Bulk density; and (4) porosity. Pine needle beds are highly porous media and bulk properties are important for analysis, as compared to solid materials where bulk properties are not required. The porosity of the sample adds multiple variables to the system that are not found in solid materials, adding another degree of difficulty to the analysis. The heat transfer relationship includes convection within the sample matrix, whereas conduction was assumed to be negligible. Gas transport in the sample and mixing of oxygen and pyrolysis gases, while not yet fully understood, is known to play an important role in the study of time to ignition.

Particle Density and Surface Area to Volume Ratio

As will be apparent in the next section the density was used in the calculation for the porosity. The density of the needles was determined by immersing a known mass of needles in a known volume of ethanol. The volume displaced by the fully immersed needles was recorded and the density calculated:

$$\rho = \frac{m_{needles,\ dry}}{V_{needles}} \tag{1}$$

where

$$V_{needles} = V_{total} - V_{ethanol} \tag{2}$$

The SVR was determined by close inspection of the needles. The geometric features of needles vary from species to species. Some needles are long and rigid other short and soft. Needles can be grouped in pairs, triplets or quintuplets on one fascicle. In case of the species studied, Pitch pine (*P.rigida*), the needles are grouped in triplets. Several assumptions were applied to the geometry of individual needle triplets such as circular shapes were used instead of oval ones to simplify calculations. Various measurements with a caliper were recorded and the SVR for each species was calculated. The calculations were based on the following:

$$SVR = \frac{\text{Surface Area}}{\text{Volume}} \tag{3}$$

The SVR is a particle characteristic that is used to compare species' geometry and shape. Large values mean that the fuel is fine, smaller values means thicker needles.

Bulk Density and Porosity

These are the properties that characterize the samples used in the experimentation. The properties provide a quantitative representation of fuel package and are important when comparing different sample conditions. The bulk density was calculated, from the sample weight (m_{sample}) and the volume of the sample holder (V_{sample}).

$$\rho^* = \frac{m_{sample}}{V_{sample}} \tag{4}$$

Bulk density and particle density (ρ) were used to calculate the porosity of the sample:

$$\alpha_{gas} = 1 - \frac{\rho^*}{\rho} \tag{5}$$

The bulk properties provide a good base of comparison of various test condition and can be used to evaluate the test results.

EXPERIMENTAL PROTOCOL AND MODIFICATIONS

The FM Global Fire Propagation Apparatus (FPA) was used in conjunction with ASTM E 2058 test procedures [19]. Two adjustments were made to adapt the protocol to the porous samples: (1) Custom

sample holders were made. These were made of 1 mm thick perforated stainless steel with 63% open area (O/A) to allow flow to enter the sample. In some tests the sides and bottom of the sample holders were wrapped in aluminum foil to create 0% open area baskets blocking the flow of air into the sample. (2) A blockage device was placed into the test chamber to prevent the inlet airflow to escape around the sample. This piece is vital in its place since it is assumed that all inlet airflow enters the sample. When the blockage device was left out the flow follows the path of least resistance and only a small amount enters the sample. This behavior was verified via particle image velocimetry (PIV) by Simeoni [16] and Schemel [15]. The inlet flow is important in many ways: it changes the heat transfer, gas transport and oxygen availability. One drawback with this blockage device is that mass loss could not be recorded because the sample holder is placed onto the device which is attached to the wall of the test chamber. See Figs. 1 and 2 for pictures and schematic.

Dead needles were packed into cylindrical sample holders by hand. The basket's diameter was 12.6 cm with a depth of 31 mm. The sample size was considered a cylinder of cross sectional area 0.0125 m^2 and 30 mm depth. The gross (including weight of water in sample) sample mass for dead needles was 15 g. An additional modification to previous procedures involved the live needle mass. For the live needles an equivalent mass load was calculated to account for the FMC. This procedure is important because it is desired to evaluate a comparable amount of combustible material. For live needle samples the FMC can be in excess of 100 %. Dry dead needles have a FMC below 10% on a dry weight basis. The following equations were used in the calculations to find equivalent sample mass, $m_{moist,live}$:

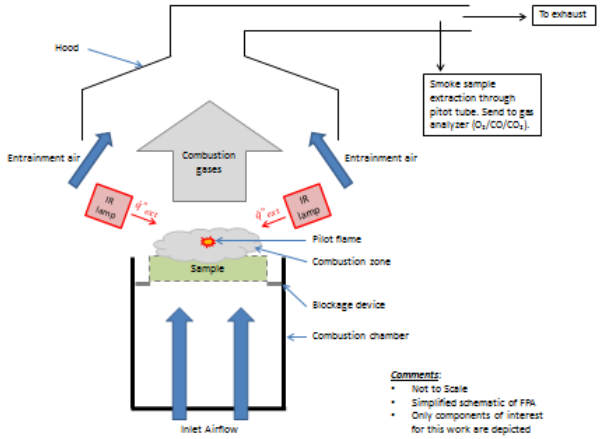

Fig. 1. Simplified schematic of FPA. Review [19] for more detailed schematic.

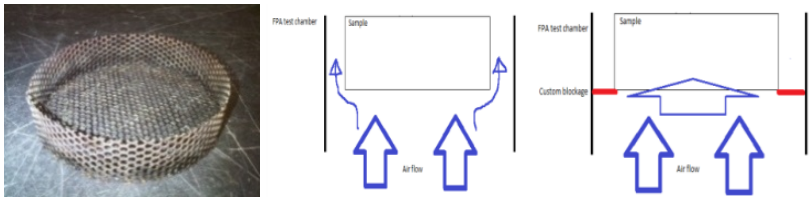

Fig. 2. From left to right: schematic of FPA; 63% sample holder; schematic of flow behavior without blockage; schematic of flow behavior with blockage.

Based on the FMC calculation on a dry weight bases

$$FMC = \frac{m_{moist} - m_{dry}}{m_{dry}} = \frac{m_{water}}{m_{dry}} \tag{6}$$

One can calculate the water mass present in the sample,

$$m_{water} = FMC * m_{dry} \tag{7}$$

Furthermore, the wet needle mass, m_{moist} is equal to

$$m_{moist} = m_{dry} + m_{water} \tag{8}$$

Finally substituting equation (7) in (8) and solving for the dry mass gives

$$m_{dry} = \frac{m_{moist}}{1+FMC_{dead}} \tag{9}$$

For dead needles having a FMC_{dead} of approx. 7.9% (*P.ri.*) the actual dry mass is 13.8 g for a total sample weight, m_{moist} of 15 g. For comparison it is desired to have the same dry mass for the live needle experiments. The calculation is as follows,

$$m_{moist,live} = m_{dry}\ (1 + FMC_{live}) \tag{10}$$

Live needles having a FMC of approx. 160% will require an equivalent sample weight of 36 g to obtain a comparable dry mass of 13.8 g. Results from the FPA tests included oxygen consumption, carbon monoxide and dioxide generation, and time parameter data. This data allowed the calculation of the evolution of heat release during the test period. The heat release rate (HRR) was calculated from oxygen consumption as outlined in [19]. The ignition behavior was considered as piloted ignition. All tests were conducted with a piloted flame. The pilot was an ethylene/air premixed flame that was kept active throughout the entire test. In this study it was not desired to determine the moisture of extinction [2] but rather force the samples to fully combust. This scenario is supported by the assumption that a wildfire can exist that is intense enough to transfer sufficient heat to an unburned fuel package in front of the fire, that it will ignite, and sustain ignition (either flaming or smoldering).

The time to ignition was obtained manually with a stop watch. Time to ignition is defined as the time from first heat exposure until flaming ignition is observed. One species was investigated: Pitch pine (*Pinus rigida*; *P.ri.*).

In order to determine the FMC of dead and live needles, samples needed to be conditioned. This was done using a muffle furnace. Samples were conditioned for 24 hours at 60 degrees Celsius and weighed before and after the conditioning period. The FMC is then calculated on a dry weight basis using Eq. (6).

In the experimentation the samples corresponding to 8% FMC are dead needle samples unconditioned. Samples with 125% and 160% are live unconditioned samples and samples at 38% are wet samples conditioned for 10 hours at 60°C. It was assumed that the conditioning temperature was sufficiently low to allow only water evaporation and with negligible degradation of the needles. The study consists of a range of experimentation performed in the FPA. Time to ignition and heat release rate parameters are commonly used to characterize the burning dynamics and hence are the parameters most important in this work. Furthermore, the combustion process was examined to identify flaming and smoldering combustion periods. The main test condition of interest is the sample's FMC. However, various inlet airflow conditions are also examined. The results are evaluated to assess the influence on the burning dynamics of moist fuel packages. The reason for continuing the study of airflow is because it is an ever present condition in the natural environment. The two tables below summarize the experiments conducted including information of the experimental conditions and species tested as well as particle and bulk properties.

Table 1. Summary of experimental conditions.

Test Type	**Heat Flux [kW/m^2]**	**Dry Sample Mass[a] [g]**	**Sample Holder [% O/A]**	**Flow Condition [lpm, cm/s]**	**Species**
FPA (ignition, HRR)	25, 50	13.8	0, 63	NF (0), LF (50, 6.7)	*P.ri.*

[a] Sample mass is a net value, equivalent mass loading is used where appropriate to account for water content.

Table 2. Summary of particle (needle) and sample properties.

Pitch pine, *P. rigida [%FMC]*	Needle Properties			Bulk Properties				
	Density[b] [kg/m^3]	SVR [m^{-1}]	FMC	Dry mass [g]	Equivalent mass [g]	Sample Volume [*10^{-3} m^3]	Porosity [%]	Density* [kg/m^3]
Dead (8)	607	7,112	0.08	13.8	15	0.375	93.5	40
Live (37)	643		0.37		19		92.2	50
Live (125)	813		1.25		31		89.8	83
Live (160)	834		1.60		36		88.5	96

[b] The following assumption was made about the density: A composite density was considered to account for the needle material and water content, $\rho_{com} = \sum_i X_i \rho_i$. Where X_i is the mass fraction. Water density of 1,000 kg/m^2 was used.

The FPA is a versatile apparatus that can be easily adapted to suit the research needs for this work. However, the heat flux wavelength distribution from the FPA is different from the one generated by wildland fuel flames [20] and [21]. There is comparison in literature about flammability tests conducted in the FPA and the Cone calorimeter (Cone). The main point of discussion is the difference of the radiative properties of the heat sources and the wavelength dependence of material properties. The Cone heating element mainly operates at a wavelength above 2.0 μm whereas the infrared lamps of the FPA mainly operate below 2.0 μm [21]. The material tested is another part of the equation: wavelength dependent reflectance and transmittance are inducing different burning behaviors in the two apparatuses for wood and clear PMMA [20]. In-depth radiation is important in this work since the pine needle samples have a high porosity. However, it is not a consequence of the material (needle) radiative properties as it is for PMMA, but it depends on the fuel sample bulk properties. The sample does not have a flat surface and flue spaces exist for radiation to penetrate it.

The wavelength dependence of pine needles was demonstrated by Monod et al. [22]. However, Acem *et al*. [23] showed that the absorptivity of a layer of dry needles was higher than the one of pine needles as a material and was close to 1 in average (see table 3). This effect should decrease the wavelength effect of the heaters.

Table 3. Spectrally averaged absorptivity for of needles and layers of *Pinus halepensis*. Conditions for an irradiation by a blackbody at 1000 K (from [23]).

Sample	Absorptivity, α
Single layer, moist	0.95
Single layer, dry	0.89
Thick layer, dry	0.95

RESULTS AND DISCUSSION

The results are evaluated with respect to the control parameters: moisture content, airflow, sample basket openness and heat flux. Unconditioned and conditioned live needles were tested as well as dead dry needles.

Throughout the experimentation it was desired to determine the drying behavior of the needles in a furnace in order to predict how long a sample should be conditioned to get a desired MC. It was found that this behavior depends strongly on the size of the samples that are being conditioned. The preliminary dehydration results (small samples < 5 g) were not comparable with dehydration behavior of the FPA samples (> 15 g). It is not of interest to test an exact MC but rather a range of values. As long as the FMC and MC can be determined for individual sample sets the results will be usable. Dehydration behavior from the conditioning will be observed with further tests optimizing the protocols with changing the sample mass and bulk density.

Most tests were conducted with open baskets and natural convection (no flow, NF) at 25 kW/m^2. The burning behavior of very moist fuels (125 and 160%) varied from dry dead fuel in that the samples did not fully combust. Virgin material was left in the basket at the end of the tests (15 min). This can be explained with several aspects: (1) the heat available (from source) was not intense enough to effectively dry and

pyrolyze the available fuel (in-depth); and (2) the oxygen concentration was diluted/displaced by the emitted water vapor. Adding these conditions together created a fuel lean gas mixture in the combustion region which could not sustain a flame.

Due to the unburned virgin material left after the tests it was assessed that a higher heat flux condition needed to be tested. It was desired to have a fully combusted sample at the end of the test to accurately evaluate the heat release rate. Therefore the heat flux was increased to 50 kW/m^2 in order to obtain data from samples that were consumed completely. This will be discussed in the subsequent section in terms of total heat released (THR). Since all samples (dry or wet) have the same amount of dry combustible material (Gross mass minus water mass) the THR should be the same for all tests.

Time to Ignition

The time to ignition increases with increasing moisture content, as shown in Fig. 3. This is due to excess water in the sample that needs to be evaporated before pyrolysis can occur. For low FMC (8 to 40%) the ignition time does not change dramatically, but when the FMC is increased the time to ignition is much longer, which can be translated to a slower fire spread rate. The comparison of the ignition behavior between low and high FMC verifies the results found by Jervis [6]. The results are on different scales due to the different sample masses and higher FMC.

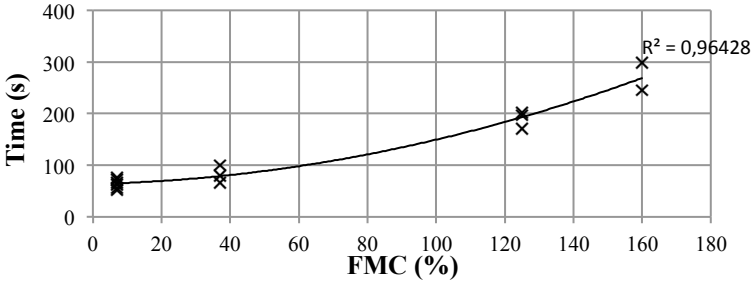

Fig. 3. Time to ignition for no flow, open basket and 25 kW/m^2 test conditions with various MC.

The time to ignition results for live sample tests indicate some similarities with dead needle tests but also some differences. The comparison in Fig. 4 for low heat flux (HF) shows that the ignition behavior is not the same. Besides the obvious difference in ignition time, an increase in the time is not clearly visible for the live needle samples and forced flow (LF) as it is for dead needle samples. A high variability for the low HF tests is due to the combination of FMC, airflow and low HF conditions. Variability decreases when the airflow and/or FMC is reduced, or the HF is increased. Another reason for the high variability is the extensive smoldering that was observed visually prior to flaming ignition. This was a typical behavior for high MC samples. Even at high heat flux condition smoldering started prior to flaming ignition although less pronounced. This behavior is further discussed in the smoldering combustion section. Tests at high HF (50 kW/m^2) were only done with live needle samples as shown (for comparison: dead needle samples at this HF have an ignition delay time around 8 seconds). The ignition time under this high HF is independent of the airflow condition and basket openness. This behavior is the same for dead needle samples as identified by Thomas *et. al*. [18].

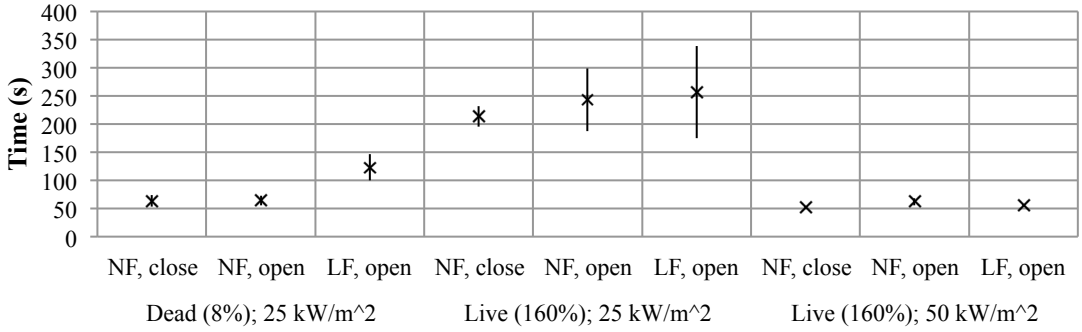

Fig. 4. Time to ignition comparing low and high external heat flux tests for sample.

The influence airflow (wind) was studied on dry dead needles. The results indicated that the time to ignition is only influenced by the airflow for low heat flux conditions where the convection cooling and the radiant external heat flux are in competition. For high heat fluxes (> 40 kW/m^2) the radiation becomes dominant over the convection rendering it negligible. This means that even the forced convection condition test has the same ignition time than the no flow, closed basket case. The wet needle samples in Fig. 4 do not behave in this manner.

Heat Release Rate

In Fig. 5 one can observe the trend of the peak HRR of the samples at various FMC. The peak HRR decreases with increasing FMC. This is attributed to the presence of increased water vapor in the combustion zone, which acts as a heat sink, as well as the incomplete combustion of samples at high FMCs. In Fig. 6 one can observe that the sample burns less completely for FMC as the THR during the tests decreases. This is the first verification that very wet samples do not burn well and need a higher external energy source to burn as intensely as the dry counterparts.

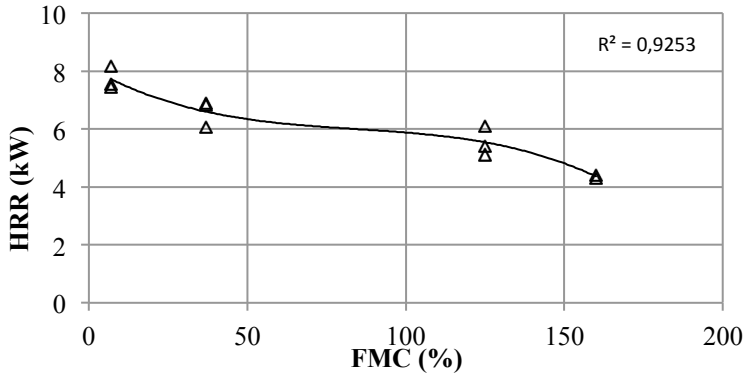

Fig. 5. Peak HRR for no flow, open basket and 25 kW/m^2 test conditions.

The following discussion compares the HRR results for the 25 kW/m^2 tests with 50 kW/m^2 tests. The results plotted in Fig. 7 show a decrease in peak HRR for each test condition when the heat flux is increased. This behavior can be explained by looking at the way the samples are heated. For the low heat flux case the sample is slowly heated, water evaporates at the surface, pyrolysis begins and a gaseous mixture accumulates at the surface. This behavior is equivalent for the high heat flux case.

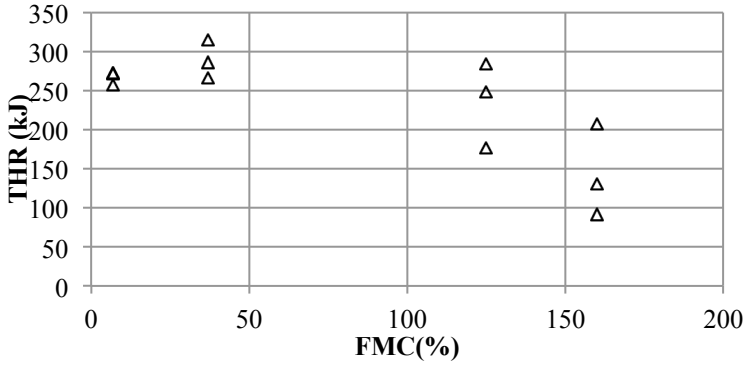

Fig. 6. Total heat released during test for no flow, open basket and 25 kW/m^2 test condition.

The main difference is that for low heat flux conditions it take longer to reach the ignition temperature compared to the high heat flux case; meaning that the gaseous mixture can continue to form for a longer period before ignition occurs. This results in an instantaneously higher peak HRR for low heat flux conditions. In addition, for high heat flux conditions, the surface of the fuel starts burning when the lower fuel layers are still drying, and supply the gas phase with a substantial amount of water vapor

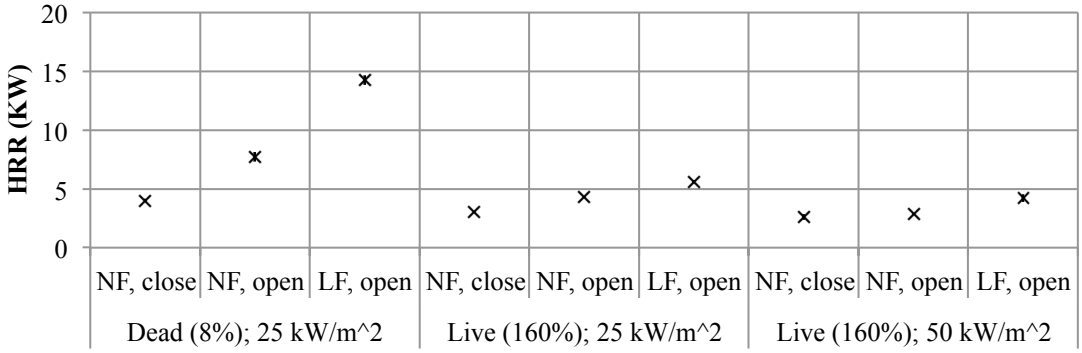

Fig. 7. Peak HRR comparing low and high external heat flux tests.

To visualize this behavior, Fig. 8 and Fig. 9 below show the heat release rate evolution during the FPA tests.

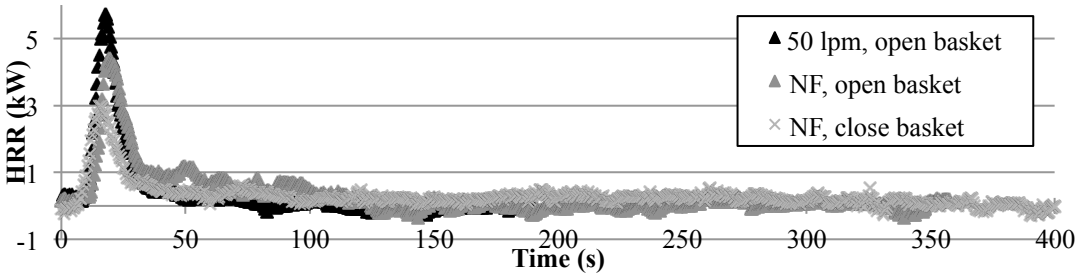

Fig. 8. Typical 25 kW/m^2 test heat release rate evolution for 160% FMC samples.

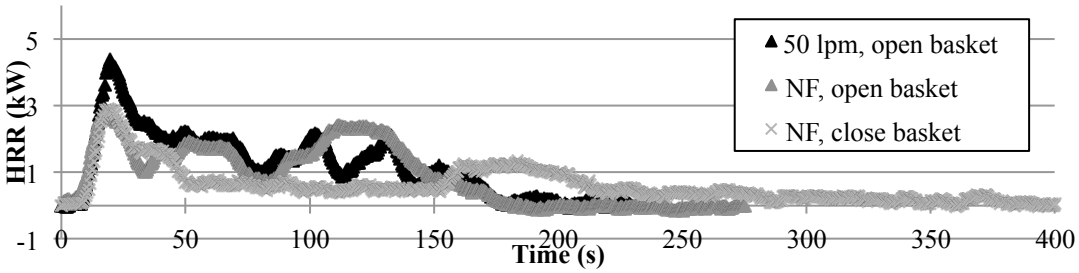

Fig. 9. Typical 50 kW/m^2 test heat release rate evolution for 160% FMC samples.

Comparing the burning behavior of these two heat flux condition one can find clear distinctions. One is, as already seen in Fig. 7, that the peak HRR is lower for the 50 kW/m^2 tests. More obviously however, the combustion period is much shorter for the 25 kW/m^2 tests. It should be noted, that time to ignition is not represented in these graphs (see Fig. 4.). In order to easily compare burning behaviors, the time to ignition of all tests was moved to zero seconds in both graphs. Furthermore, times of flaming ignition are not presented because for the higher heat flux case continuous flaming was not obvious. The ignition behavior can be best explained as a short period of continuous flaming followed by a longer flashing period. For all tests the pilot flame was present for the entire duration of the test.

To further evaluate this burning behavior, the THR is presented as verification that not all material was consumed in the low heat flux tests. In Fig. 10, one can observe that the combustion behavior for dead dry samples at 25 kW/m^2 and live wet at 50 kW/m^2 follows similar trends. Whereas the live wet samples tested at 25 kW/m^2 show a different behavior. If the wet samples at lower heat flux combusted completely the behavior would be similar to the others. This is clearly not the case and it is confirmed that a significant external heat source is needed to combust the live wet needle samples. Since all samples contain the same amount of combustible material it was first assumed that the THR must be the same for each airflow condition. This is not the case. The deviation between the NF, close basket and LF, open basket condition

can be attributed to the combustion behavior. When the basket is closed oxygen availability is limited at the combustion region, which is at the surface of the sample.

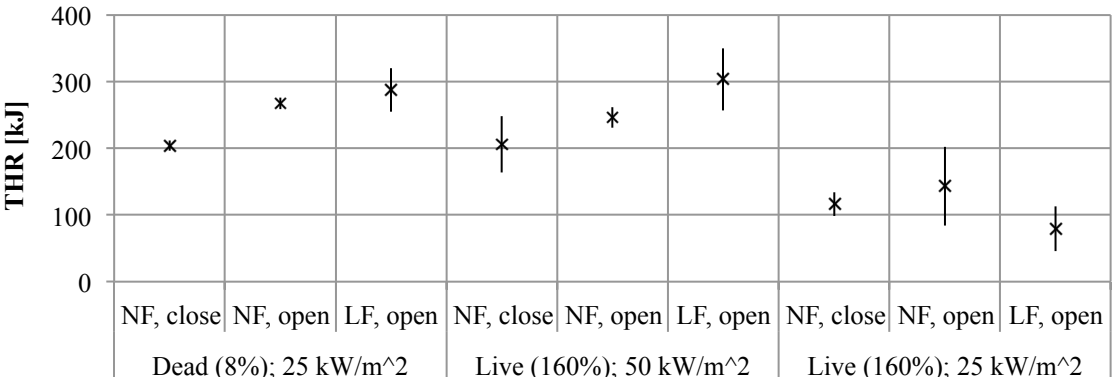

Fig. 10. Averaged total heat release comparison for dead and live needles at 25 and 50 kW/m^2.

While the sample burns, its surface and with it the combustion region regresses below the rim of the sample holder. This further limits the mixing of oxygen and pyrolysis gases and results in a more incomplete combustion. When the sample holder is open, oxygen is readily available around (and inside) the sample and the combustion process is more complete. This behavior will be further evaluated in the following section in terms of differentiating between flaming and smoldering combustion.

Smoldering Combustion

While performing the experimentation with wet samples, it was first visually observed that the high FMC promoted smoldering ignition. In order to verify this observation the CO and CO_2 data was analyzed. As above the results were evaluated with respect to the test conditions, close/open sample basket, flow condition and moisture content. Flaming ignition and smoldering ignition is distinguished by indicators in the CO and CO_2 curves. A complete combustion with less smoldering can be identified by a high CO_2 and low CO concentration. When the CO concentration indicates a rise it is representative of an increase in smoldering combustion.

The three graphs below, Fig. 11, Fig. 12, and Fig. 13 show the CO and CO_2 generation for dead needle samples under three different test conditions regarding the basket open area and the flow condition (all at 25 kW/m^2). Immediately, one can recognize the increase in peak CO_2 concentration when oxygen availability increases, i.e. the basket is open and airflow is forced into the sample. The CO concentration peaks for all cases around 40 to 50 ppm, however the shape of the CO curve changes. This means that the conditions for smoldering combustion are influenced. For no flow and close baskets a flaming period with little smoldering can be seen (140 to 200 sec.). From 200 to 260 seconds a transition period can be seen in which flaming and smoldering combustion occur simultaneously followed by flame extinction and an increase in smoldering.

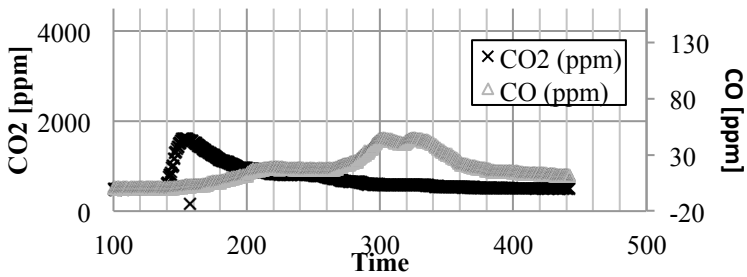

Fig. 11. CO and CO_2 Concentration for dead needle, NF, close basket tests.

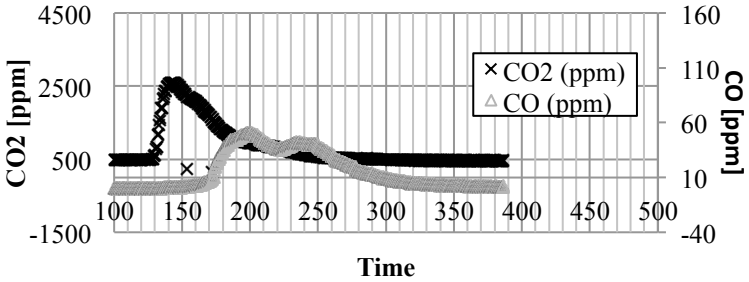

Fig. 12. CO and CO2 Concentration for dead needle, NF, open basket tests.

The length of the transition period decrease when the basket is open and natural convection within the sample is effective. Flaming combustion period occurs from 125 to 160 seconds followed by a short transition period until 180 seconds and only smoldering after. The last case, Fig. 13, where the airflow is forced into the sample, no purely flaming combustion region is visible. Combustion begins with both flaming and smoldering simultaneously. The behavior explained above corresponds well with visual observations that led to this analysis, concluding that airflow promotes simultaneous combustion. This behavior was already observed by Schemel [15]. Furthermore, this effect becomes important in understanding the behavior of ember generation as it was also observed that small embers were expelled from the samples for the forced flow conditions.

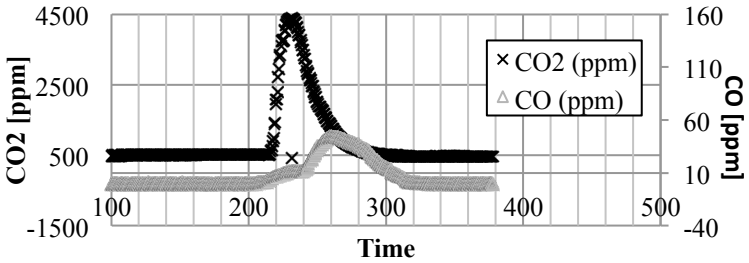

Fig. 13. CO and CO2 Concentration for dead needle, LF, open basket tests.

To better understand the influence of FMC on smoldering the combustion behavior of needle bed samples was evaluated for various FMC values. The tests were conducted at 25 kW/m^2 with open baskets and natural convection (NF). The three graphs, Fig. 14, Fig. 15, and Fig. 16 show the concentrations for three FMC in increased order. The results from dead needle sample tests (8% MC) under the same test conditions can also be used for this analysis, which is represented in Fig. 12.

Comparing the peak concentrations one can observe a decrease in the CO_2 peak concentration from 2500 to 1900 to 1600 to 1400 ppm for 7, 37, 125 and 160% MC tests, respectively. The reverse behavior is true for the CO concentration which peak at 50 ppm for 7% samples, 100 ppm for 37% samples, 140 ppm for 125% samples, and 110 ppm for 160% samples. The latter, Fig. 16, behaves out of the ordinary with a decrease in CO peak concentration. This is attributed to the onset of smoldering ignition prior to flaming ignition.

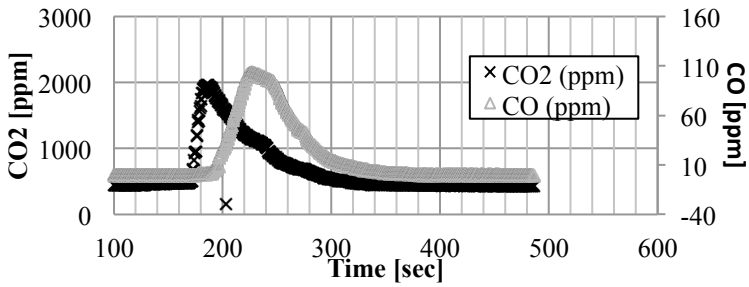

Fig. 14. CO and CO2 Concentration for live needle sample at 37% MC.

In Fig. 14, low FMC samples display a short flaming combustion that can be recognized with the delayed rise of the CO concentration. A transition period is still visible until flames extinguish at around 240 seconds followed by the pure smoldering combustion period. As the FMC increases the purely flaming combustion period shortens and smoldering combustion becomes the dominant reaction. In the case of the highest FMC (Fig. 16), one can observe that smoldering ignition occurs before flaming ignition. This scenario was also observed visually. Flaming ignition is inhibited by the water vapor when the FMC is high, which was also shown by the low peak HRR for moist fuels. This results in a slow, low intensity smoldering fire behavior which can have a long lifetime.

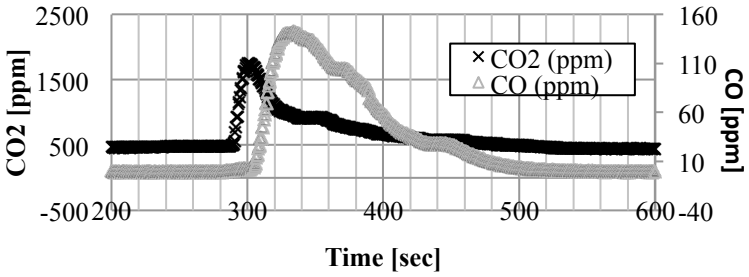

Fig. 15. CO and CO2 Concentration for live needle sample at 125% MC.

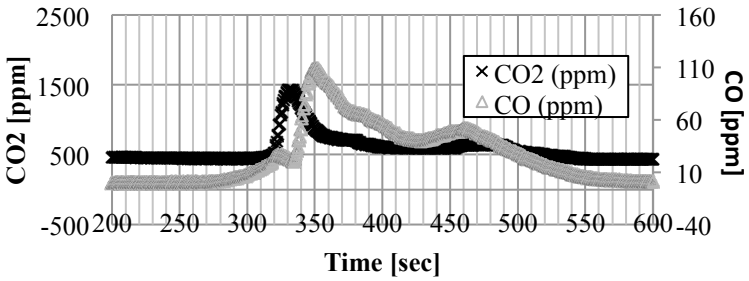

Fig. 16. CO and CO2 Concentration for live needle sample at 160% MC.

CONCLUSIONS

This experimental study contributes to increase the general knowledge on burning behavior of forest fuels. The laboratory experiments were performed using the FM Global Fire Propagation Apparatus with modifications to its equipment and protocols in order to accommodate the special use in the field of wildfire research. Porous pine needle samples (*P. rigida*) were subjected to a broad range of experimental conditions, such as sample basket openness, airflow condition and external heat flux. However, the main conditional parameter of interest was the fuel's moisture content and its influence on the burning dynamics of the needle bed. The results presented include time to ignition, heat release rates, total heat released, and CO/CO_2 concentrations. The analysis focused on the influence of the moisture content on these flammability parameters and additionally the smoldering combustion potential for wet forest fuels. The findings can be summarized:

- The time to ignition increases with increasing fuel moisture content due to the excess water in the sample that needs to be evaporated before sufficient pyrolysis gases can be produce that will form a combustible gas mixture.
- The ignition behavior for wet live needle samples is similar to dry dead needle samples with respect to the modes of heat transfer. For low heat fluxes the convection cooling of a forced airflow (wind) has influence on the time to ignition. However, for high heat fluxes the radiation becomes dominant over convection.
- The peak heat release rate decreases with increasing moisture content. This is attributed to the presents of increased water vapor in the combustion zone, which acts as a heat sink, as well as the incomplete combustion of samples at high moisture content.

- The total heat release measurements were used to evaluate the combustion process of the samples to supplement the previous conclusion. At the heat flux tested, 25 and 50 kW/m^2, it was found that the lower flux is not substantial enough to allow complete combustion of the samples with high water content. This indicates that an intense fire is required in order to prevent the extinction of the fire.
- The oxygen availability is limited when the sample holders are only open at the top resulting in incomplete combustion process. This can be extended to a larger scale sample where the oxygen is only available at the borders and not in the center of the sample.
- Smoldering combustion is affected by a forced airflow (wind) and sample moisture content. For no airflow condition flaming and smoldering combustion occur consecutively. When airflow is introduced they occur simultaneously. High fuel moisture contents inhibit flaming combustion and promote long smoldering combustion periods.

To fully understand the combustion processes and flammability characteristics of forest fuels more laboratory testing needs to be performed. The environmental conditions influencing the burning behavior of vegetative fuels are abundant and must be assessed individually by decoupling them from each other through laboratory analysis. This work is yet another step leading the way to broaden the knowledge about the wildfire phenomenon.

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