

Flammability Study of Pine Needle Beds

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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 study is a continuation of previous flammability studies [1, 2]. In these studies dead needle beds were characterized and the influence of imposed airflow conditions, representing wind, on the burning dynamics were studied to understand flammability parameters such as the heat release rate and ignition time. The methodologies applied in the previous studies were improved with some modifications. Furthermore, fuel moisture content was added as an experimental parameter for wildland fuel flammability investigation because it is representative of live fuels which burn when crowning conditions develop. In general an increasing flow increases the flammability as peak heat release rates increase [3]. However, for low heat flux condition (representing low intensity, slow moving fire) the flow increases the time to ignition, due to cooling and mixing, hence lowering the hazard. Increased moisture content in needle litters favors smoldering decreasing the intensity and hence lowering the hazard. However it can create embers with a longer lifetime that can be picked up by the wind and act as ignition sources. This creates a different hazard that should be accounted for in the characterization. This work highlights the driving role of airflow and fuel moisture content on wildland fuel flammability. Each one individually drives fuel flammability in a different way and their combination has a variable influence in fire hazard. It is the intent of this research to deliver a detailed analysis of the importance of the main fuel and environmental parameters on the burning behavior of wildland fuels.

KEYWORD: Wildland fires, flammability, calorimetry, forest fuels species, fuel moisture content, burning dynamics

NOMENCLATURE:

<i>a</i>	apparatus dimension (m)	<i>SVR</i>	surface area to volume ratio (m ⁻¹)
<i>d</i>	dead needles	<i>t</i>	time (s)
<i>FMC</i>	total fuel moisture content on dry basis (24h conditioning)	<i>V</i>	Volume (m ³)
<i>HF</i>	high flow (100 lpm)	Greek	
<i>HRR</i>	heat release rate	<i>α</i>	volumetric ratio
<i>LF</i>	low flow (50 lpm)	<i>ρ</i>	density (kg/m ³)
<i>l</i>	live needles	Subscripts	
<i>lpm</i>	liters per minute	<i>dry</i>	dry mass of needles
<i>m</i>	mass (kg)	<i>gas</i>	volumetric ratio of gas (porosity)
<i>MC</i>	moisture content (<24h conditioning)	<i>H₂O</i>	water
<i>NF</i>	no flow (0 lpm)	<i>initial</i>	initial mass
<i>P.r.</i>	<i>Pinus resinosa</i> (Red pine)	<i>wet</i>	wet mass of needles
<i>P.ri.</i>	<i>Pinus rigida</i> (Pitch pine)	Superscripts	
<i>P.s.</i>	<i>Pinus strobus</i> (White pine)	() [“]	per unit area (m ⁻²)
<i>q̇</i>	heat flux (kW/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. Many empirical, semi-empirical as well as physical models have been developed that evaluate wildfire behavior. The fire hazard is normally associated with the fire intensity and rate of spread. 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 fuels differ by a great extent since the value can be extremely 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 understood in great detail in order to make use of fully developed physical models.

One can make an analogy to a fire in the realm of solid material. 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 build. 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 laboratory experimentation is used in the flammability characterization for solid material it is suitable that similar processes are used for vegetation.

As this is a continuation of previous flammability studies it is the intent to improve the experimental protocols with additional modifications. It became clear that a large amount of experimentation was necessary in order to fully recognize the burning dynamics and what influences an imposed flow and the fuel moisture content have.

PARTICAL 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 to Volume Ratio (SVR)

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:

$$\rho = \frac{m_{\text{needles, dry}}}{V_{\text{needles}}} \quad (1)$$

where

$$V_{needles} = V_{total} - V_{ethanol} \quad (2)$$

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 or triplets on one fascicle. In case of one species (*P.s.*) they are grouped in quintuplets. Several assumptions were applied to the geometry of individual fascicles 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:

$$SVR = \frac{Surface\ Area}{Volume} \quad (3)$$

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

Bulk Density and Porosity

These were the properties that will characterize the samples used in the experimentation. It related the contrast between a fuel package representing a litter from the ground or a volume from the crown. The bulk density was calculated, from the sample weight (m_{sample}) and the volume of the sample holder (V_{sample}).

$$\rho^* = \frac{m_{sample}}{V_{sample}} \quad (4)$$

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

$$\alpha_{gas} = 1 - \frac{\rho^*}{\rho} \quad (5)$$

EXPERIMENTAL PROTOCOL AND MODIFICATIONS

The FM Global Fire Propagation Apparatus was used in conjunction with ASTM E 2058 test procedures [4]. 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 air flow to escape around the sample. This piece is vital in its place since we claim the assumption that all inlet air flow enters the sample. When the blockage device was left out the flow will follow the path of least resistance and only a small amount will enter the sample. This behavior was verified by previous studies [1, 5]. One drawback with this blockage device was that mass loss could not be recorded because the sample holder touches the device which was attached to the wall of the test chamber. See Fig. 1 for pictures and schematics.

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 and 30 mm depth. The loading weight for dead needles was 15 g per sample. An additional modification to previous procedures involved the live (moist) needle mass. For the live needles we calculated an equivalent mass load to account for the high fuel moisture content (FMC).

This procedure is important because it is desired to evaluate a comparable amount of material that is actually flammable. For the live needles the FMC can be in excess of 100 %. Dry dead

needles have a FMC below 10% on a dry basis. Equations (6) and (7) were used in the calculations to find equivalent live needle mass:

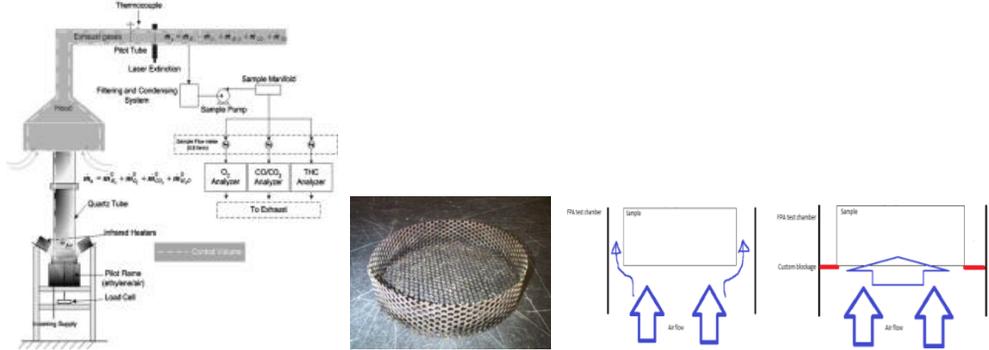


Figure 1. From left to right: schematic of FPA; 63% sample holder; schematic of flow behavior without blockage; schematic of flow behavior with blockage.

For the dead needles the actual dry mass is calculated as,

$$m_{dead, FMC} = m_{dead, sample} (1 - FMC_{dead}) \quad (6)$$

where $m_{dead, sample}$ is the selected sample mass including water. For dead needles having a FMC of approx. 7.9% (*P.ri.*) the actual dry mass is 13.8 g for a total sample weight of 15 g. The same dry mass must be used for the live needle experiments. The calculation is as follows,

$$m_{live, FMC} = m_{dead, FMC} (1 + FMC_{live}) \quad (7)$$

Live needles having a FMC of approx. 160% will require a total 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) from oxygen consumption was calculated as outlined in [4].

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 was observed. The period of flaming combustion was recorded for some experiments. Three species were investigated: White pine (*Pinus strobus*; *P.s.*), Red pine (*Pinus resinosa*; *P.r.*) and Pitch pine (*Pinus rigida*; *P.ri.*). These species vary in geometric features and particle properties (size, number of needles per fascicles and density).

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 (total water content) is then calculated on a dry weight basis:

$$FMC = \frac{m_{wet} - m_{dry}}{m_{dry}} 100 \quad (8)$$

Furthermore, it was desired to study samples at different moisture contents (MC). This required the conditioning of live needles for less than 24 hours. A study was conducted to analyze the dehydration behavior of live needles at ambient air and in a furnace. Samples of live needles were left at ambient condition. The weight was recorded incrementally and the data was plotted to visualize the behavior. Also, samples were conditioned in a furnace for 2, 4, 6 ... 24 hours. Their mass was recorded and MC calculated:

$$MC = \frac{m_{H_2O}}{m_{dry}} \quad (9)$$

where

$$m_{dry} = \frac{m_{initial}}{1-FMC} \quad (10)$$

$$m_{H_2O} = m_{wet} - m_{dry} \quad (11)$$

FPA test samples were prepared and placed in the furnace and conditioned for a certain amount of time according to preliminary dehydration results. For example, a sample with 130% FMC has a MC of approximately 50% after 6 hours conditioning at 60 degrees Celsius. After the sample's conditioning period, to create a sample with a desired MC, they were tested immediately. An additional sample was added to be kept in the furnace to obtain the FMC of this set of samples. This was necessary as the total water content is used in the calculations for the MC.

This study consists of a range of experimentation with different focal points. Time to ignition and heat release rate parameters are most commonly used to characterize flammability and hence are the parameters most important in this work. One part of the study focused on the time to ignition of dead needles with only the influence of an airflow as an experimental parameter. These experiments were done mainly with *P.s.* and *P.r.* species. The second part included the FMC as an additional parameter; these were done with *P.ri.* Species. 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]	Sample Mass ^a [g]	Sample Holder [% O/A]	Flow Condition [lpm]	Species ^b
FPA (ignition only)	20 - 60	15	0, 63	NF (0), LF (50), HF (100)	<i>P.s.</i> , <i>P.r.</i>
FPA (ignition, HRR)	25	15	0, 63	NF (0), LF (50)	<i>P.r.</i> , <i>P.ri.</i> (d), <i>P.ri.</i> (l)

^a Sample mass is a nominal value, equivalent mass loading is used where appropriate to account for water content.

^b the letters (d) and (l) indicate dead and live needles; for *P.s.* and *P.r.* species only dead needles were used

Table 2. Summary of particle and bulk properties.

Species	Needle Properties		Bulk Properties	
	Density [kg/m ³]	SVR [m ⁻¹]	Porosity [%]	Density* [kg/m ³]
White pine, <i>P.s.</i>	621	14,173	94	40
Red pine, <i>P.r.</i>	776	7,024	95	40
Pitch pine, <i>P.ri.</i> (d)	607	7,295	93	40

RESULTS AND DISCUSSION

The results are evaluate with respect to the control parameter: (1) an airflow; and (2) moisture content on the flammability of porous samples.

Influence of Airflow

For the first portion of the experimentation the results from the ignition tests with *P.s.* and *P.r.* needle samples will be analyzed and are plotted in Fig. 2.

The data is portrayed in this fashion (one over the square root of the ignition time vs. external heat flux) because for solid material the time to ignition is proportional to one over the heat flux squared [6]. A straight line on this graph represents the ignition behavior of a solid material.

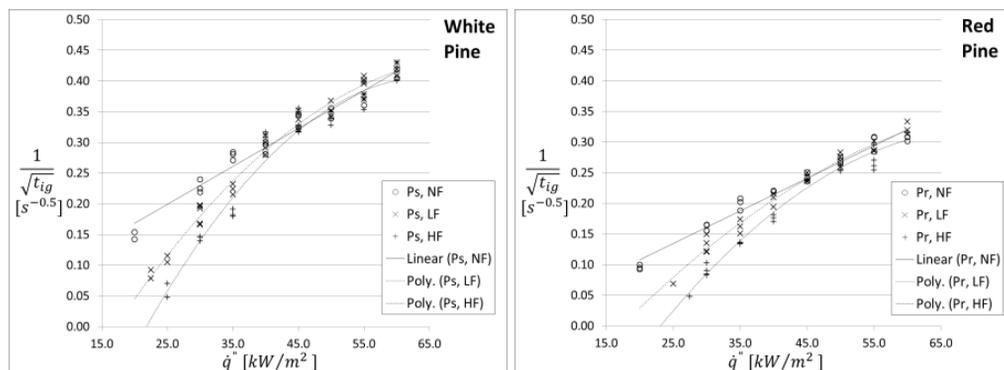


Figure 2. Time to ignition experiment results for White pine (left) and Red pine (right).

Knowing this behavior it can be deduced that the results for no flow and closed baskets have a solid like ignition behavior. When the baskets are open and an airflow is imposed this behavior changes. The airflow introduces a convection cooling affect within the sample which increases the ignition time. This influences the heat transfer which consists of the external radiation and the convection within the fuel matrix. For one flow condition the convection stays constant whereas the radiation is increased. For both species there exists a point at which the radiation becomes dominant over the convection. This is identified as the convergence of the data at a certain external heat flux. For *P.s.* samples this occurs at 40 kW/m^2 and *P.r.* samples at 45 kW/m^2 . Translating this into terms describing a hazard one can say that airflow only reduces the hazard for low intensity fires (low external heat flux).

The airflow has a second effect on the ignition. It changes the gas transport within the sample and the combustion zone. The flow provides a steady supply of oxygen into the combustion zone. This can be considered as a constant for one flow condition. The changing variable is the pyrolysis gas production rate which increases with increasing heat flux. From the results no clear tendency can be seen. But it can be assumed that there exists a potentially best condition, a balance between air flow magnitude and heat flux that will result in a fast mixing and best ignition. As mentioned previously the convection effects are small at high heat flux which means that the gas transport has to be the reason for this fast ignition for high flow conditions. Further experiments will be required in order to have a clear conclusion on this matter.

In another set of experiments the influence of an air flow on the time to ignition was evaluate at one heat flux, 25 kW/m^2 . Here Red (*P.r.*) and Pitch pine (*P.ri.*) was used as the sample fuel. The flow conditions tested here were no flow (NF) and low flow (LF) with closed and open baskets. The results of are plotted in Fig. 3 and 4.

As determined earlier, the convection affects are clearly visible at lower heat flux conditions. The results from these tests verify this behavior. Furthermore it was found that no flow (natural convection) conditions with close or open baskets have similar results. It can be concluded that the natural convection created from buoyancy effects is small compared to the forced flow (LF).

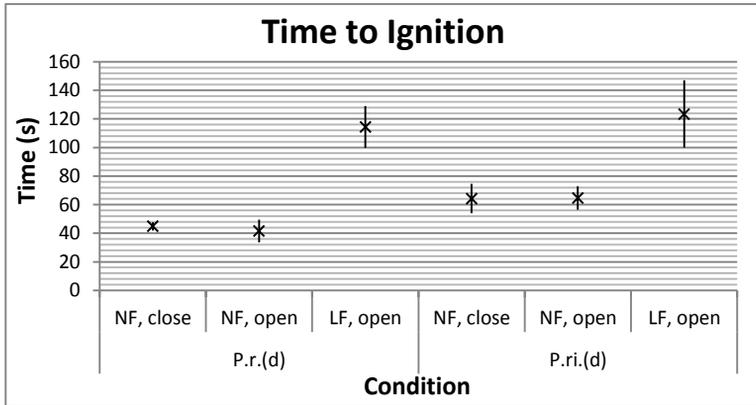


Figure 3. Time of ignition comparison for dead Red pine and Pitch pine samples for various flow conditions.

In the same portion of this study the HRR was found for these two species at the same experimental conditions. This provides the second aspect of the flammability characterization and what the influence of airflow is. Below is a representation of the peak HRR.

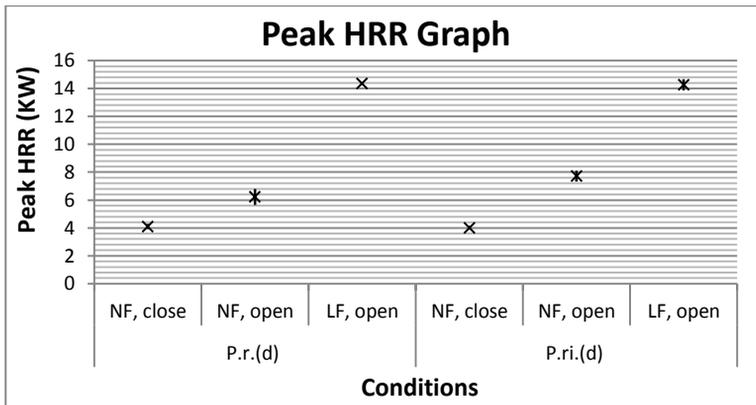


Figure 4. Peak HRR comparison for dead Red pine and Pitch pine samples for various flow conditions.

The influence of the flow on the peak HRR is clearly visible. The intensity increases with increasing flow condition. Interestingly, the natural convection with open baskets does show a significant increase. This illustrates that both parameters, time to ignition and HRR must be considered in the flammability characterization, i.e. the time parameter did not show a change in the hazard potential whereas the intensity of a potential fire increased by 50 to 100% from no flow close baskets to open baskets. Even a low forced flow increased the peak HRR by 300%.

Another view of this increase of the hazard is shown in Fig. 5. These graphs are typical HRR curves from the FPA experiments for *P.r.* and *P.ri.* samples as compared above. The intensity increases rapidly when the flow is increased. When the peak HRR is used as a characterization of the flammability a clear rise of hazard potential can be realized.

The time of flaming can also be used as an indication for hazard potential. This will add more insight to the burning behavior of the samples. Figure 6 shows the time of flaming ignition. Even though it was determined that an increased air flow will increase the hazard in terms of peak

HRR, the results show that the time of flaming ignition drastically decreases with increasing flow condition.

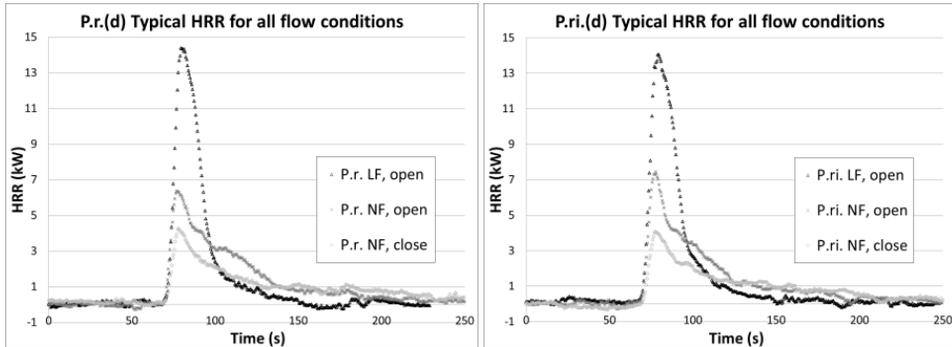


Figure 5. Typical HRR curves for *P.r.* (left) and *P.ri.* (right).

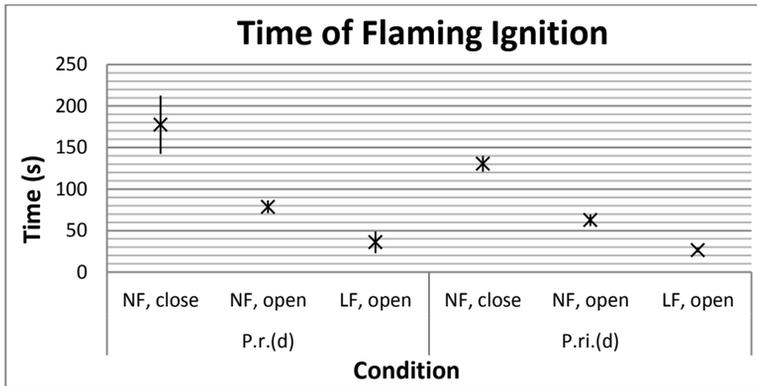


Figure 6. Time of flaming ignition comparison for dead Red pine and Pitch pine samples for various flow conditions.

Influence of Fuel Moisture Content

The FPA tests with live needles were conducted with *P.ri.* species. FMC results revealed a range of 120 to 180% (on dry basis) depending on the time when the needles were collected. Unconditioned and conditioned live needles were tested. The results are represented in Fig. 7 and 8 with respect to their FMC.

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. This behavior depends strongly on the size of the samples that are being conditioned. Sample sizes used to find the FMC were in the range of 2 to 5 g (wet mass). Whereas the sample used in the FPA tests had a wet mass of approximately 31 g. Samples with a FMC of approximately 125% were conditioned for 10 hours at 60 °C and resulted in a MC of 37% when the initial prediction for the MC was 15 to 20%. This deviation is due to the size of the sample and the bulk density. 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.

The influence of the MC on the flammability is again evaluated with HRR and time to ignition parameters. Figure 7 clearly indicates a decrease in the peak HRR with increasing MC. All tests

were conducted with open baskets and natural convection (NF) in order to eliminate these two experimental conditions. 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. This can be explained with several aspects: (1) The heat available (from source) was not enough to pyrolyze the available fuel, the radiation could not penetrate far enough into the sample due to the decreased porosity (approx. 86% due to higher equivalent mass); (2) the buoyancy forces were not strong enough to carry pyrolysis gases from the center of the fuel matrix to the top surface; and (3) the oxygen 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. In terms of hazard characterization it can be concluded that the hazard decreases when looking at peak HRR for live moist needles. Extensive smoldering ignition after the flame extinguished was observed as the virgin material continued to smolder for a long time. Hence the hazard from embers becomes greater as the MC promotes a development of embers with longer lifetime.

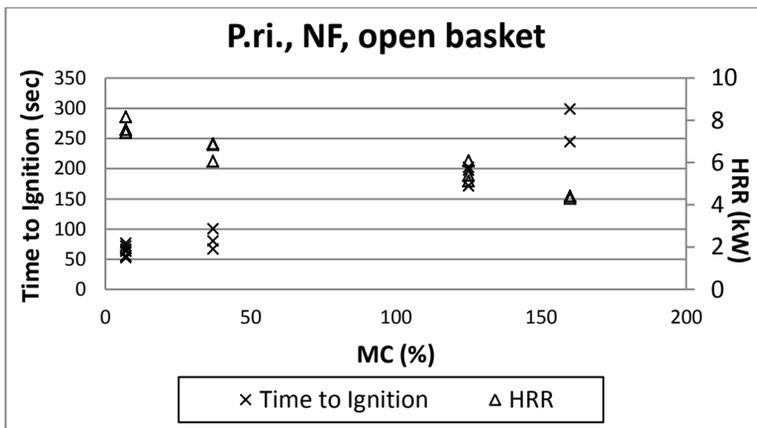


Figure 7. Peak HRR and Time to ignition comparison for live Pitch pine at various MC.

Looking at time to ignition it is intuitive that the time increases with increasing MC as more water must be evaporate before ignition conditions develop. The results shown in Fig. 7 above verify this behavior.

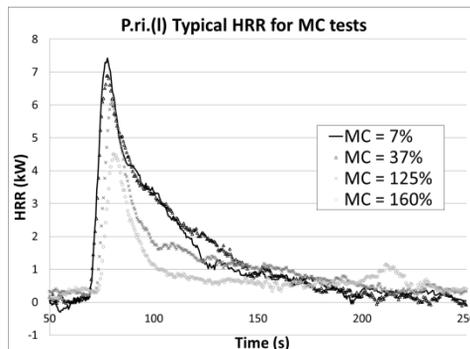


Figure 8. Typical HRR curve for P.ri. sample at various MC.

Figure 8 shows the burning behavior of live *P.ri.* samples (7% sample is dry dead needles). The nature of the high MC curves verifies that not all material was burned as the area under the curve (total energy released) is smaller than the curves for low MC tests.

CONCLUSIONS

Recapturing all the evidence from the experiments discussed above it can be concluded that an airflow – representative of wind – and moisture content – representative of live needles – influence the burning behavior of vegetation greatly. However it cannot be said that wind solely increases the hazard potential for a fire involving vegetation. The moisture content study is a representation of wet environmental conditions as well as fires with crowning potential involving live needles. Summing up the finding from FPA experimentation:

Imposed airflow:

- Time to ignition increases with an increased airflow; this only holds true for low intensity fires.
- The peak HRR increases with an increased airflow.
- The residence time of flames decreases with increased airflow.

Fuel moisture content:

- Time to ignition increases with increasing MC.
- Peak HRR decreases with increasing MC even with using equivalent mass.
- Potential for smoldering increases with increasing MC.

The difficulty is to gauge what is the most important factor to consider in the hazard analysis. It is clear that all parameters should be used in a flammability characterization. When one is neglected the resulting analysis can be misleading and might not provide a valid conclusion for a given fire scenario. When combining the observations from both factors discussed above it can be deduced that the hazard potential increases because (1) the peak HRR increase by 300% with a wind but only decreases by 50% with a high MC; and (2) the time to ignition increases more than 100% with a flow and 500% with a high MC, however it was also shown that this is only valid for low intensity fires. Therefore, the HRR parameter can be identified as more important in a flammability characterization.

ACKNOWLEDGEMENT

This work was partially funded by FM-Global and the USDA Forest Service (JVA no. 12-JV-11242306-123).

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