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A CALORIMETRIC STUDY OF WILDLAND FUELS

C. Schemel^{}, A. Simeoni^{***}, H. Biteau^{*}, J. Torero^{*}**
cschemel@packereng.com

***BRE Centre for Fire Safety Engineering, University of Edinburgh, Edinburgh,
Scotland, UK**

****Packer Engineering, Inc., Columbia, Maryland, USA**

*****CNRS-SPE, University of Corsica, Corte, France**

Abstract

The burning of two species of pine needles: *Pinus halepensis* and *Pinus pinaster*, was studied to characterize the behavior of the forest floor in wildland fires. These fuels are representative of the Mediterranean ecosystem and have very different shapes and surface-to-volume ratios. Calorimetry was performed using the FM-global fire propagation apparatus (FPA). To better understand the effects of transport in the fuel beds, the standard sample holder was replaced by a holder that allowed for the porous properties of the fuel to be studied in a systematic manner. These holders were designed with holes on the surface to allow for different air flow rates to pass through the holder and into the fuel sample. These characteristics created different internal fuel bed conditions and were the first such tests that could be identified that examined transport on this level in these types of wildland fuels. Tests were conducted under natural convection and forced flow. The test series results were analyzed with respect to the direct values of the measured variables and calculated values of heat release rate. Discrete variables of time to ignition, duration of flaming combustion and peak heat release rate were compared using an analysis of variance method. As the experiments were conducted under well-ventilated conditions, the heat release rate calculated by calorimetry was compared to mass loss rate and heat of combustion. CO concentration in time proved to be a good indicator of the combustion dynamics in the fuel bed. Heat release rate, time to ignition and time to reach peak heat release rate indicated a strong dependence on flow conditions and on fuel specie. It was shown that the transport processes in the fuel beds had a significant effect on the burning characteristics.

1. Introduction

The need to understand the combustion characteristics of wildland fuels is currently a matter of great urgency to wildland fire professionals. As buildings and other human activities increasingly encroach into wildland areas, the impact of wildland fires on human endeavors is acquiring greater importance. This impact usually manifests as loss of life, loss of property and the use of resources in fire mitigation efforts. To help manage these increasing risks and better understand wildland management issues, improved assessment tools need to be developed. The precision of wildland fire assessment tools is limited by the understanding of many key variables.

The understanding of the fuel dependent behavior and other parameters affecting combustion are of great importance. Heat release rate (HRR) of a fuel is among the most important parameters for understanding combustion process, fire characteristics and propagation rates. It serves to define parameters such as flame geometry and temperature fields.

Many difficulties exist when analyzing wildland fuels. Obtaining repeatable calorimetry data for wildland fuels is difficult because of the number of parameters that significantly affect uncertainty associated with the HRR [1]. Weise et al. [2] compared methods of oxygen consumption calorimetry to measure the flammability characteristics of several types of

vegetation in two calorimeters; a cone calorimeter and an intermediate scale bio-mass calorimeter. The work of Weise et al. illustrates many of the complications involving consistency of HRR results when using cone calorimetry to characterize wildland fuels.

The parameters of concern are not only associated with testing issues, such as experimental methodology and fuel configuration, but also to fuel origin, (i.e. moisture content or chemical composition). Although wildland fuels are largely living or dead bio-mass where the general chemical composition is well defined [3], they also include a number of specific components that have not been properly identified or characterized for each individual material. These minor components and other environmental variables can have a significant impact on a fuel's burning characteristics. Furthermore, most test conditions do not map well to real fire scenarios and, therefore, gaps exist between HRR data and useful applications for that data in real problem solving. Many of the problems associated with the definition of the HRR data for wildland fuels are the same as those appearing when assessing standard fuels and the extrapolation of test data to the modeling of real fires.

A study involving two Mediterranean pine needles is presented in this paper. Pine needles present a clear fire hazard in the Mediterranean region by providing a continuous fuel matrix across the forest floor. Whilst other shrubs and crown fires contribute to wildland fire intensity, forest floor fuels, like pine needle beds, sustain wildland fires and provide for the greatest extent of fire spread [4]. Detailed research into characterizing fire spread in pine needle beds has taken place over the past years. Porterie et al. [5] described the level of detail required for modeling porous fuel beds accounting for the hydro-dynamic effects inside the fuel bed, prediction of detailed kinetics and products of combustion. Most recent experimental work in this area concentrates on the bulk behavior of the fuel bed for various external conditions, such as, slope [6], plume velocities and temperature profiles [7] but very limited effort has concentrated on the characterization of pine needles as a fuel.

This paper studies several variables associated with the uncertainty of calorimetry when applied to wildland fuel characterization. The test results provide data describing how two types of pine needle varieties behave during combustion under specific, controlled conditions. The test conditions allow the internal porous fuel bed characteristics to be examined. By controlling the fuel sample holder basket opening and combustion air flow rate during the tests, mass transport characteristics were varied systematically. This approach allowed for an analysis of the dynamics of HRR and products of combustion relative to flow conditions in the fuel bed.

2. Calorimetric Calculations

Oxygen consumption calorimetry is a convenient and widely used method for measuring the amount of heat release for a laboratory scale fire test [8]. The HRR from a fire can be calculated from the amount of O₂ consumed by the combustion process [9]. The HRR is calculated using the following equation:

$$\dot{q} = E_{O_2} (\dot{m}_{O_2}^0 - \dot{m}_{O_2}) \quad (1)$$

In general, several simplifying assumptions are associated with the calculation of HRR by oxygen consumption and carbon dioxide generation calorimetry. All gases are considered to behave as ideal. The apparatus used for the HRR calculations in the test series presented in this paper were conducted at atmospheric pressure lending validity to this assumption. The amount of energy released by complete combustion of an organic fuel per unit mass of O₂ consumed is constant at 13.1 kJ g⁻¹ [10].

Combustion air contains only O₂, H₂O, CO₂, and N₂. All inert gases were assumed to have the properties of nitrogen. Prior to measurement in the experimental apparatus, the combustion exhaust gases were dried. The mole fraction of O₂ (CO₂, CO, total hydrocarbon)

in the exhaust flow is different from the one measured in the analyzer and was calculated using the following equation:

$$Y_{O_2} = (1 - Y_{H_2O}) Y_{O_2}^A \quad (2)$$

The only exhaust gases considered were O₂, H₂O, CO₂, CO and N₂. They were assumed to represent for over 99% of the exhaust gases in almost all fire tests [8]. Nitrogen does not participate to the combustion reaction and is conserved, allowing the assumption presented in the following equation:

$$\dot{n}_{N_2} = \dot{n}_{N_2}^0 \quad (3)$$

Water vapour production during combustion is not considered in the calorimetry calculation. In the absence of a measure for water vapour in the exhaust gases the molecular weight of the exhaust gases are assumed equal to the molecular weight of the incoming air. The flow rate is measured by mean of a Pitot tube. It is evaluated by the pressure drop across the device as indicated in the following equation::

$$\dot{V}_e = K A \sqrt{\frac{2\Delta P}{\rho_e}} \quad (4)$$

The density of the exhaust stream is given by the following equation:

$$\rho_e = \frac{P_{duct}}{RT_e} M_e \quad (5)$$

The parameter ϕ is defined as the depletion factor. It is the fraction of the incoming air that is fully depleted of its oxygen during the combustion process. It is calculated using the following equation:

$$\phi = \frac{\dot{n}_{O_2}^0 - \dot{n}_{O_2}}{\dot{n}_{O_2}^0} = \frac{Y_{O_2}^{A^0} (1 - Y_{CO_2}^A - Y_{CO}^A) - Y_{O_2}^A (1 - Y_{CO_2}^{A^0})}{Y_{O_2}^{A^0} (1 - Y_{O_2}^A - Y_{CO_2}^A - Y_{CO}^A)} \quad (6)$$

α is the expansion factor. During a combustion reaction, a fraction of the incoming air is depleted of its oxygen and is replaced by an equal or larger number of moles of combustion products. The expansion factor is the ratio of these two molar quantities. It is given by the following equation:

$$\alpha = 1 + Y_{O_2}^{A^0} (1 - Y_{H_2O}^0) (\beta - 1) \quad \beta = \frac{\sum n_{stoichio\ products}}{n_{stoichio\ O_2}} \quad (7)$$

To simplify the calculation, an average value for the expansion factor α is assumed to be equal to 1.105 with a maximum relative error of 10% [11].

3. Experimental Method

The FM-global flame propagation apparatus (FPA) was used to conduct the test series presented in this paper [12]. Its basic layout is presented in Fig. 1. The FPA operates on a similar concept to a cone calorimeter. A fuel sample is radiated and an ignition source provided. The mass loss rate of the sample is measured and the exhaust gases are analyzed for composition, temperature, optical obscuration and pressure drop across an orifice plate. One key difference with the FPA in comparison to the cone calorimeter is that the combustion chamber for the sample allows for a controlled environment with respect to gas flow rate and composition.

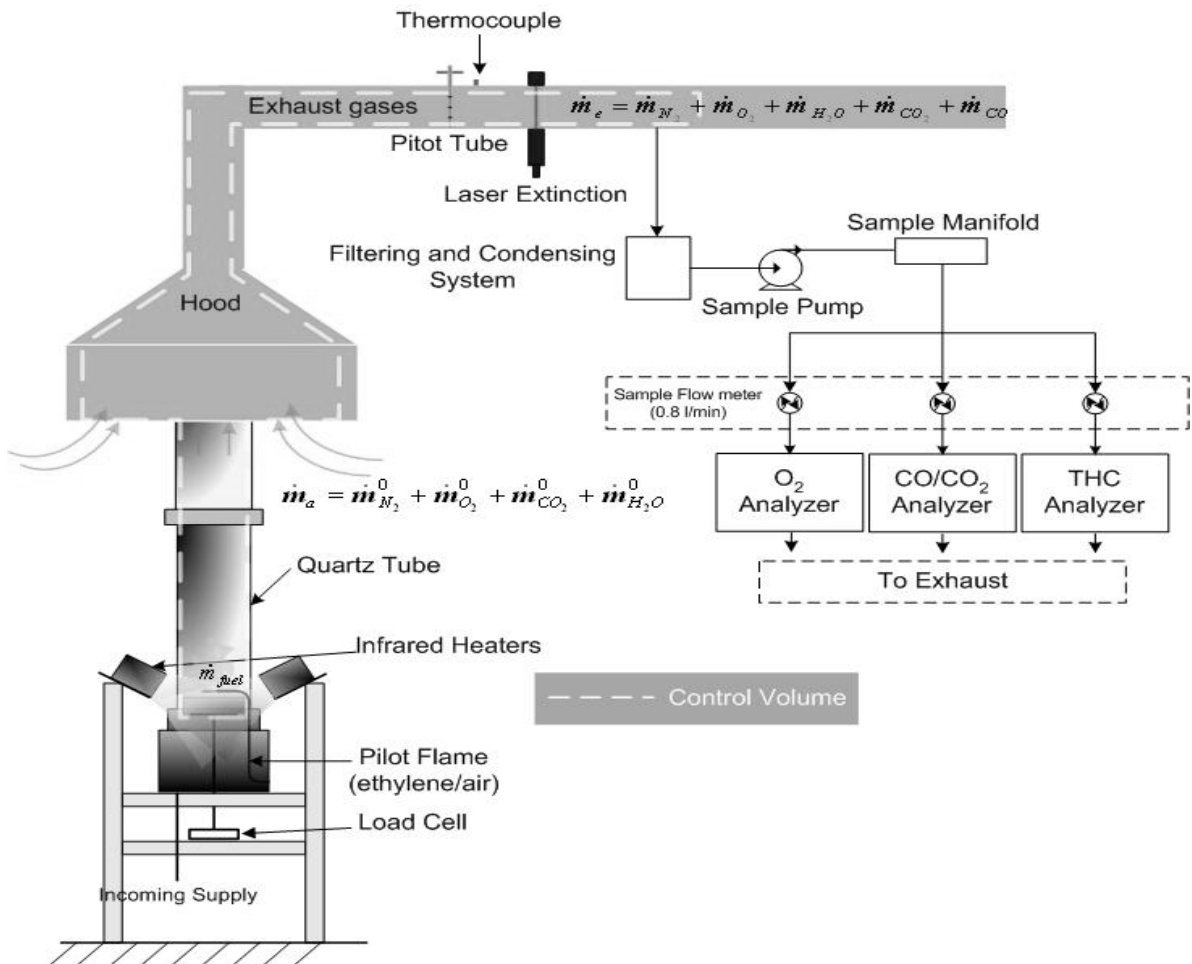


Figure 1. Overview of the FPA system.

The combustion chamber and the sample holder for the FPA are cylindrical. The sample holder fits inside the combustion chamber and is positioned on a balance. Specific sample holders were designed for this test series and are pictured in Fig. 2. They were made of stainless steel and had uniform, small holes in all (side and bottom) of the outside surfaces of each holder. These holes created an open space for inlet combustion gases to pass into the holders and through the fuel samples. Baskets were also lined with aluminum foil to provide for a no internal flow condition for the fuel bed, either natural convection or forced air.

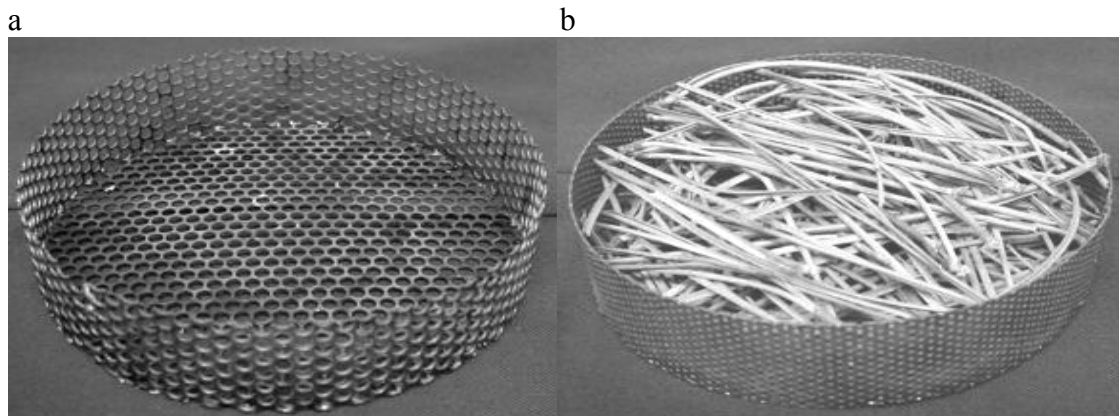


Figure 2. Sample baskets; a) 63% open basket, b) 26% open basket with *Pinus pinaster*

The two fuels studied in this test series, *Pinus pinaster* and *Pinus halepensis*, were collected from Mediterranean wildland areas. The needles were dead and not conditioned prior to testing. The moisture levels of the needles were determined by oven drying of a sample for 24 h at 60 °C. The surface to volume ratio for *P. pinaster* was 4260 and 9170 m⁻¹ for *P. halepensis* with an approximate 15% error [11].

The experiment was designed to test each pine needle species in three sample holders allowing different airflows at both natural convection and forced combustion air flow conditions. The baskets were filled to the top and had a constant mass of 15 g. The needles provided one experimental factor (fuel) with two levels (*P. pinaster* and *P. halepensis*). The baskets were a second experimental design factor (porosity) with three levels (0%, 26% and 63% opening). A third experimental design factor was flow of air to the combustion chamber. The flow control allowed for two levels to the fuel sample; natural convection (no-flow) and forced combustion air (flow). A single value of 200 l/min for the forced air flow was used and supplied to the combustion chamber. The precise value of the flow through the fuel bed samples was not directly measured. A camera was positioned to observe the behavior of the pine needle bed during combustion. Each test condition was repeated three times for a total of thirty test runs. The test matrix is presented in Table 1.

Table 1. Experimental design

Test Number	Fuel Type	Basket Opening	Combustion Air Condition
1-3	Pinus Pinaster	0%	Natural Convection
4-6	Pinus Halepensis	0%	Natural Convection
7-9	Pinus Pinaster	26%	Natural Convection
10-12	Pinus Pinaster	26%	Forced Flow
13-15	Pinus Halepensis	26%	Natural Convection
16-18	Pinus Halepensis	26%	Forced Flow
19-21	Pinus Pinaster	63%	Natural Convection
22-24	Pinus Pinaster	63%	Forced Flow
25-27	Pinus Halepensis	63%	Natural Convection
28-30	Pinus Halepensis	63%	Forced Flow

4. Results and Discussion

4.1. Statistical analysis of the results

The test series was analyzed with respect to the direct values of the measured variables and calculated values of HRR. In addition to the continuous variables of gas concentrations and fuel mass measured during the test runs, the discrete variables of time to ignition, duration of flaming combustion and peak HRR were also analyzed.

The statistical analysis of the discrete data was done using an analysis of variance (ANOVA) and based on the experimental design shown in Table 1. In short, ANOVA is a method that compares measured variables for given set of experimental conditions to determine if the mean values are significantly different. The factors and levels for this experiment were: fuel type, *P. halepensis* or *P. pinaster*, basket opening, 0%, 26% or 63%; and combustion air, flow or no-flow. The experiments were designed so the factors were repeated three times at each level. Significance of a test result was determined, as in many statistical tests, by selecting a confidence level, e.g. 95%, about the mean. In the ANOVA this confidence level is determined by a calculated probability statistic based on an assumed F-distribution. The

probability statistic is analogous to confidence intervals using the tails of a normal distribution.

ANOVA is a valuable analysis method in this type of parametric testing because it allowed inferences about test parameters to be examined both individually and in combination. ANOVA is also valuable for evaluating systems that may have a high degree of uncontrolled variation, as in wildland fuels and porous fuel beds. A well designed experiment allows for conclusions to be made about the effect of controlled parameters by measuring variables of interest at all combinations of test conditions. The tests presented here used a full factorial design with three replications. The analysis of this experiment and the conclusions are valid as a level effect, but not a detailed empirical model. The consistency of the experiments allowed for high confidence (>99%) levels to be used in determining test condition effect on the measured mean values.

In Table 2, some of the calculated results of the ANOVA are presented as an example. The first column shows the test condition of combustion air flow or no-flow. The second column shows the mean value of all tests repeated under the condition indicated in the first column with the standard deviation of the sample means (standard error of the estimate) in parenthesis. The final column reports the number of trials included in the mean, for example the number of tests conducted at the flow or noflow condition.

A combined ANOVA was run to determine if the test conditions, either alone or in some combination, had an effect on the peak HRR. When all test conditions were analyzed, only the combustion air (flow or no-flow) condition had a significant effect by itself on peak HRR. Taken in combination, however, fuel type and combustion air flow had a significant effect on HRR. The basket percent opening was a significant parameter only when combined with flow condition and fuel type. Fuel type combined with combustion air also had a significant effect on peak HRR.

Table 2. Factor: Combustion air flow condition effect on peak HRR

Factor(s)/Level	Mean Value of Peak HRR (SEE) [kw/m²]	n
Flow	12.893 (0.264)	12
No-flow	8.695 (0.187)	18

Table 3 shows the ANOVA results for time to ignition. Each test condition had a significant effect on time to ignition. The basket opening at the 26% level had the shortest time to ignition. The variance in the time to ignition was believed to be linked to the heterogeneous nature of the porosity of the fuel bed. While radiative heating during the tests was homogeneous across the surface of the samples, the porous matrix structure had significant spatial variations. This condition resulted in non-homogenous absorptivity, as well as variable convective pyrolysis gas flows. The result was thought to be localized heating and non-homogenous gas concentrations generated by the fuel bed degradation during the pre-ignition time. Thus, the relative placement of the pilot flame with respect to the localized heating and gas mixing may have resulted in time to ignition variation. These were parameters that were not controlled during the experiment. It was unclear in some of the tests if the ignition was piloted or unpiloted. Unpiloted ignition would account for some of the variability of ignition times.

The time of burning (flame out) was also analyzed by ANOVA. The flame out time was significantly shorter for both P. pinaster and the forced flow condition, individually. In combination the fuel type with basket opening had an effect, as did fuel type with flow condition on flame out. The basket opening with flow condition had an effect on flame out

time with the 26% opening basket for both the flow and no-flow conditions having the shortest flame out times.

The inference from the statistical analysis of the peak HRR, time to ignition and flame out time all indicated a dependence on the flow/no-flow condition. The other test parameters of basket opening and fuel type effected the measured variables, but not with the same consistency as the flow/no-flow condition. Both basket opening and fuel type have an effect on the beds ability to move air through the fuel sample, but the air moving through the sample was the greatest predictor of HRR and flame out time. Time to ignition was effected at each test condition. The 26% open basket may have an optimal flow condition for time to ignition and flame out. The transport processes inside the bed had a significant effect on the combustion process.

Table 3. Combustion air flow, basket opening and fuel effect on time to ignition

Factor(s)/Level	Mean Value of Time to Ignition	Standard Error	n
Combustion Air/ Flow	106 sec	4 sec	12
Combustion Air/ No-flow	53 sec	3 sec	18
Basket/0	79 sec	6 sec	6
Basket/26	68 sec	4 sec	12
Basket/63	90 sec	4 sec	12
Fuel/Halepensis	69 sec	4 sec	15
Fuel/Pinaster	89 sec	4 sec	15

4.2. Analysis of the time-dependent results

Fig. 3 shows the HRR estimated in two different ways for given conditions with no-flow and flow. The first HRR estimation was done by oxygen depletion from the O₂, CO and CO₂ measurements. The second method was done using the mass loss rate and a value for the heat of combustion obtained independently. Mass loss rate was obtained from mass loss measurements taken during the tests. These measurements were noisy so the mass loss was smoothed to decrease the oscillations. An ultimate analysis provided the elemental components of *P. halepensis* and allowed calculating the heat of combustion: $\Delta H_c = 185,000 \text{ kJ/kg}$ [14]. The value for *P. pinaster* was very close and can be assumed equal. The HRR was corrected to take into account incomplete combustion. This was done on the basis of CO measurements.

A comparison between the two methods of analysis indicated accuracy under the test conditions. The same level of repeatability demonstrated in Fig. 2 was found for all test runs with the source of most discrepancies probably being the mass loss measurements. The load cell did show some uncertainty during the test and the discrepancies in the predicted HRR were due mainly to a noisy mass loss signal. Noisy mass loss rate signals are a well known problem in calorimetry experiments especially for small masses as the ones used here [15]. Nevertheless, the “Heat of Combustion” curves overestimate the “Calorimetry” curves at the first stage of combustion and underestimated them after this point. This behavior could be due to different heats of combustion for flaming and smoldering. The heat of combustion for a gas is lower than the combustion of embers [16]. The mean heat of combustion underestimates during flaming combustion and over estimates during combustion of embers.

The experiments performed in the FPA during this test series were well ventilated; only ash remained in the sample basket after test runs (around 0.5 g). The 0% opening baskets had a very small amount of char residue (<0.5 g). Under such well ventilated conditions the two methods for HRR measurement provided equivalent results.

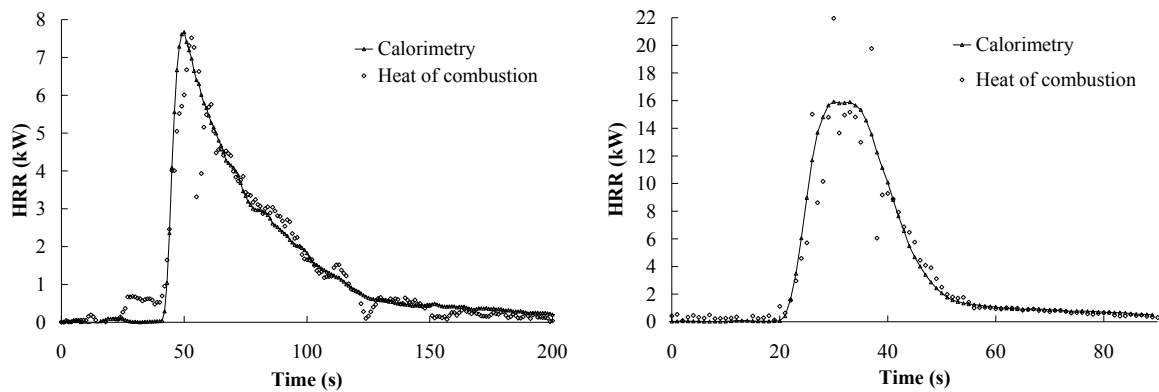


Figure 3. Mean heat release rates by oxygen consumption calorimetry and total heat release for *Pinus halepensis* and 26% opening basket – a) no-flow b) flow

Fig. 4 illustrates the typical combustion behavior for a set of test runs (three repetitions). The data was consistent within each set of test conditions for the entire test series. This was reflected in the repeatable estimates for the HRR showed in Fig. 4 a. The HRR was calculated using O_2 , CO_2 and CO values, therefore, the repeatability of the HRR was also an indication of the repeatability of all the measured gas concentrations. The vertical lines indicate the minimum and maximum time to flameout for the test runs.

In the following section, the results are discussed using the measured results of the time curves and visual observations made during the tests. The tests were videotaped; however, the light from infrared heaters prevented seeing the embers in the fuel bed. The visual observations were completed using cone test observations for the same conditions of natural convective flow [17] that were also taped.

In Fig. 4 b, the points of ignition and flameout can be seen relative to the HRR and O_2 concentration. At the point of ignition, the O_2 concentration drops steeply because of the onset of flaming combustion. The flame grows for approximately 10 s before beginning to decrease. The flame extinguishes (flameout) after another ~120 s. Glowing combustion continues beyond the disappearance of the gas flames. The HRR continues to drop off at a different, but relatively constant rate as the remaining embers burn.

Fig. 4 c shows the behavior of CO_2 and CO during a typical test run. At the ignition point both CO_2 and CO generation rates increase. As the fuel was consumed greater amounts of char and ash were formed. The flame degraded toward extinction and the CO_2 generation rate peaked and then decreased rapidly. CO generation approached the flameout point and became constant at extinction. This general behavior was seen for all test runs with some differences for flow conditions. This aspect is discussed in detail further in this section. As smoldering combustion proceeded, the CO production increased and then fell off until the embers extinguished. At that point the CO generation rate increased.

The mass loss rate is illustrated in Fig. 4 d and showed that 80-90% of the mass was lost before flameout. The amount of charring materials in pine needles is estimated at ~40% [18], therefore, the combustion of embers started prior to flameout. The flame was observed decreasing in height and radius, allowing more O_2 to reach the edge of the fuel bed and facilitated the surface reaction. The last decrease of mass was observed as the ember zone decreased to the centre of the sample holder and extinguished.

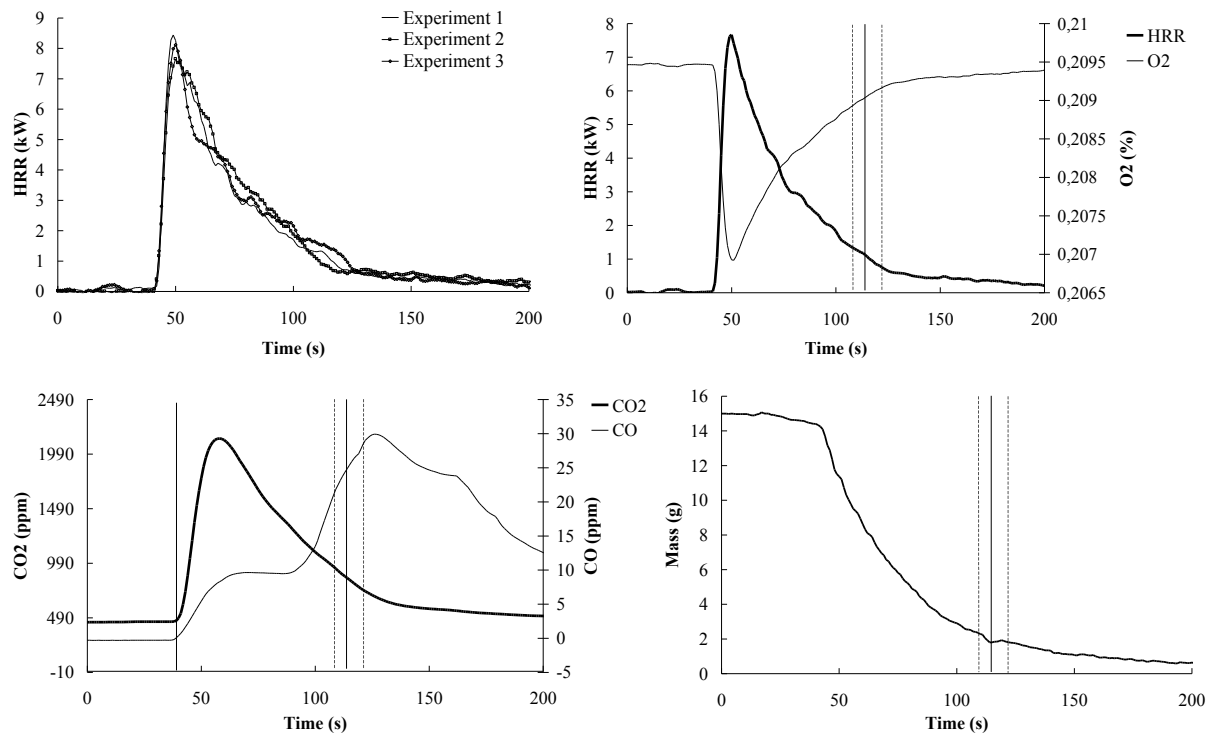


Figure 4. Burning of three samples with no-flow and 26% opening baskets for *Pinus halepensis* needles – a) three repetitions b) mean O₂ consumption and mean heat release rate c) mean CO₂ and CO productions d) mean mass loss

Fig. 5 contains the HRR curves for all of the tests including both types of needles. Fig. 5a shows the no-flow condition and indicates that the peak HRR was reached at approximately the same time, independent of species and the basket opening. The magnitude of the HRR was affected by the basket opening with the 63% basket having the highest value and the 0% having the lowest HRR. This tendency was stronger with *P. halepensis* and attributed to the higher surface-to-volume ratio. This parameter affected the internal fuel bed and impacted thermal transfers and surface area for contact with oxygen. *P. pinaster* also exhibited a higher HRR for a given flow condition.

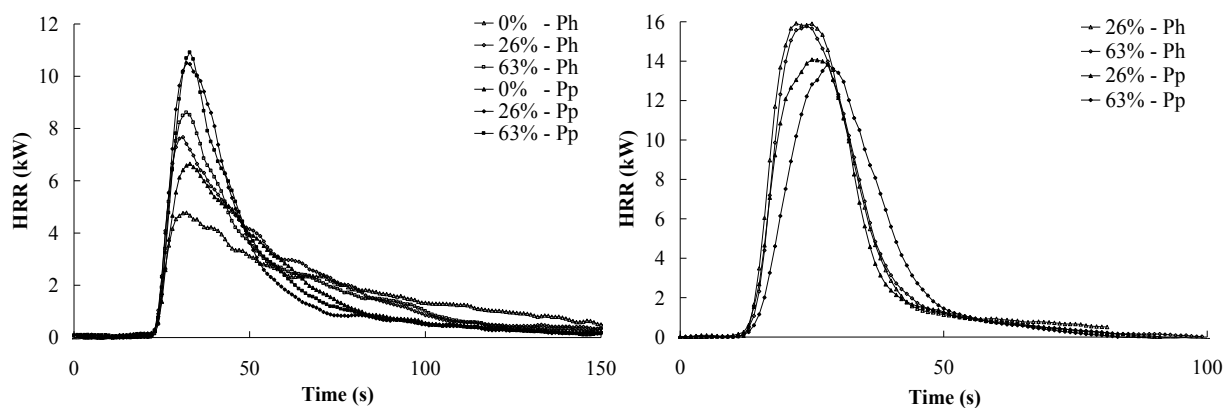


Figure 5. Mean heat release rates for the different baskets with *Pinus halepensis* and *Pinus pinaster* – a) no-flow b) flow conditions

Fig. 5 b shows the HRR estimate for the flow conditions, indicating that the flow has an effect on both the time to reach peak HRR and the magnitude of the HRR. The tendencies are

reversed for peak HRR and *P. pinaster* exhibited an influence of the basket opening on the time to reach peak HRR. This effect could be due to the changing in the inlet flow through the fuel bed as the needle beds are less dense and cooling by fresh air was allowed. With *P. halepensis*, as the flow was driven by the dense fuel bed, the opening of the basket has no effect.

Fig. 6 presents CO₂ and CO production for different test conditions. The conditions presented here demonstrate, along with Fig. 4c, changing in behavior of the combustion process. CO concentration was a good indicator of the fuel bed behavior with respect to the dynamics of flaming versus glowing combustion. The following descriptions were made of different behaviors: impermeable basket, natural convection and with flow for Fig. 6a, Fig. 4c and Fig. 6b, respectively.

Fig. 6a illustrates the no-flow and a 0% opening basket. The CO₂ curve reflects a long time of flaming combustion (around 130 s). The CO curve provides insight to the different steps involved in the combustion of the fuel samples when correlated with the observations. The first step increase was due to the ignition of the sample on the upper surface. A steady production of CO follows. During this step, the burning front spread from the top to the bottom of the basket. When this spreading ended, no more degradation gases were produced and the flame extinguished. Then, oxygen was able to reach the surface of the charred material and combustion of embers within the fuel bed started. The last decrease in the CO curve corresponded to the extinction of all combustion in the sample.

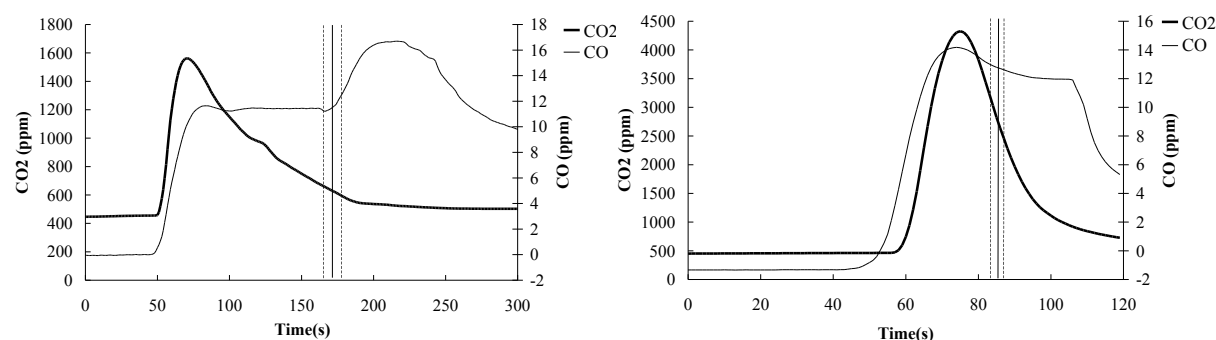


Figure 6. Mean CO₂ and CO concentrations for *Pinus halepensis* needles – a) no-flow and 0% opening b) no-flow and 63% opening c) flow and 26% opening

In Fig. 4c, the steady step was shorter than the one for no-flow conditions (see Fig. 6a). This was mainly due to an increased spreading of the flame through the fuel bed. The bottom of the bed was ventilated as natural convection through the fuel bed was allowed thanks to the open basket. The short steady step and the two slopes in the consecutive increase of CO (before and after the line representing flame extinction) are mainly due to the overlap between flaming and char combustion. The combustion of embers started on the edges of the fuel sample before flameout, leading to an increase in CO production.

Fig. 6b describes the 26% opening basket and flow conditions.

The CO₂ curve demonstrates a short time of combustion (around 40 s). The steady state disappeared. We observed a fast phenomenon with embers starting to burn before the end of the flame spreading through the fuel bed. This behavior was mainly due to the additional oxygen supplied inside the fuel bed by the forced flow.

5. Conclusions

We conducted FPA tests on pine needles samples with sample holders designed to allow the porous nature of the fuel to be studied during the tests. The goal of this test series was to help

characterize the pine needle beds with some detail as forest floor fuels. The test series exhibited a high level of repeatability for each test condition. Repeatability is difficult to attain in calorimetry using wildland fuels. The repeatability of these test runs demonstrates the usefulness of the techniques used in this test series. The application of the FPA and the use of sample holders that allow internal fuel bed flow seem to increase reliability of the test data.

The HRR calculated by means of calorimetry was reinforced by the use of mass loss rate and heat of combustion in the well-ventilated test conditions. CO concentration profiles proved to be a good indicator of the dynamics of the combustion process. The transition between flaming combustion and glowing embers was reflected in the measured CO responses. Again, the ability for combustion air to flow into the porous bed allowed the measured CO concentrations to provide good data on internal fuel bed dynamics.

HRR, time to ignition and time to reach peak HRR indicated a strong dependence on flow conditions within the fuel bed. The pine needle species studied behaved differently due to different packed densities and different surfaceto- volume ratios.

The test series and the results presented here seem to indicate that the transport processes inside the bed have a significant impact on the combustion process within the porous fuel bed. Further test are necessary with smaller opening baskets and denser fuel beds to confirm the flow effects and the fuel bed effects, respectively. An important new step to study the role of kinetics will be to use air with different oxygen concentrations.

Nomenclature

A	cross-sectional area of the exhaust duct, m^2
E	energy release per unit mass, kJ/kg
K	Pitot tube coefficient
M	Molecular weight, $g.mol^{-1}$
\dot{m}	mass flow rate, $kg.s^{-1}$
n	number of moles
ΔP	pressure drop in the Pitot tube, Pa;
q	heat release rate, kW
T	temperature, K
Y	molar fraction
ρ	Density, $kg.m^{-3}$
ϕ	oxygen depletion

Subscripts

a	incoming gas
e	exhaust gas

Superscript

A	measured analyzer value
0	initial condition

Acknowledgments

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