Study of the influence of fuel load and slope on a fire spreading across a bed of pine needles by using oxygen consumption calorimetry

V. Tihay, F. Morandini, P.A. Santoni, Y. Perez-Ramirez and T. Barboni
SPE– UMR 6134 CNRS, University of Corsica, Campus Grimaldi, BP 52, 20250 Corte, France
E-mail: tihay@univ-corse.fr

Abstract. A set of experiments using a Large Scale Heat Release Rate Calorimeter was conducted to test the effects of slope and fuel load on the fire dynamics. Different parameters such as the geometry of the flame front, the rate of spread, the mass loss rate and the heat release rate were investigated. Increasing the fuel load or the slope modifies the fire behaviour. As expected, the flame length and the rate of spread increase when fuel load or slope increases. The heat release rate does not reach a quasi-steady state when the propagation takes place with a slope of 20° and a high fuel load. This is due to an increase of the length of the fire front leading to an increase of fuel consumed. These considerations have shown that the heat release can be estimated with the mass loss rate by considering the effective heat of combustion. This approach can be a good alternative to estimate accurately the fireline intensity when the measure of oxygen consumption is not possible.

1. Introduction
Modelling has become an essential tool in forest fire research and is now a crucial instrument in forest management [1-2] as well as in the studies of risk mapping [3] and fire propagation [1-2, 4-5]. However, the accuracy of wildland fire assessment tools is limited by the understanding of key parameters such as topography and vegetation properties. It is therefore necessary to perform experiments to study the influence of these parameters on fire dynamics. In studies on the effects of fuel load [6-9] and slope [6, 9-13] on fire behaviour, the authors have mainly investigated the rate of spread, the flame height and the flame temperature. A preliminary study under no slope conditions [14] underlined the interest of studying the fire behaviour through the heat released. Yet, the heat release rate (HRR) allows understanding the combustion processes and characterizing the properties of a fire. It is used for example to determine the geometry of the flame and temperature fields for open fires [15], to classify vegetation and to understand the role of transport in porous fuel beds [16]. In the present work, we propose to investigate the effect of the slope and the fuel load on the propagation of a fire across a bed of Pinus pinaster needles by using a Large Scale Heat Release Rate Calorimeter (LSHR). We focused principally on the most relevant quantities used in forest fire science: the geometry of the flame front, the rate of spread, the mass loss rate and the heat release rate.
2. Experimental

2.1. Experimental device

The fire spread experiments were conducted by using a 1 MW Large Scale Heat Release Rate Calorimeter (LSHR). Fire tests were performed on a 2 m long and 2 m wide combustion table located under a 3 m × 3 m hood with a 1 m³/s extraction system (Fig. 1). Two thermocouples recorded the temperature of the combustion gases in the exhaust smoke duct. The bench was located on a load cell (sampling 1 Hz and 1 g accuracy) in order to record the mass loss over time during the fire spread. In order to filter the signal, a low-pass filter was applied to the mass loss measurements. Needles of *Pinus pinaster* oven dried at 60 °C for 24 hours were used as fuel. Their properties are summarized in Table 1. The net heat of combustion $\Delta H_{c,net}$ was derived from the gross heat of combustion measured in an oxygen bomb calorimeter following the standard AFNOR NF EN 14918. The surface to volume ratio $\sigma$ and the density $\rho$ were measured following the methodology proposed by Moro [17]. Ambient conditions and fuel moisture content ($p_M$) were measured for each test just before the ignition. The ambient temperature and relative humidity ranged respectively from 18 °C to 21 °C and from 35 % to 49 % for all the tests. The fuel moisture content ranged between 5 % and 10.8 % with a mean value equal to 6.8 %.

![Figure 1. Experimental device.](image-url)

### Table 1. Fuel properties

| $\Delta H_{c,net}$ (kJ/kg) | $\sigma$ (m⁻¹) | $\rho$ (kg/m³) |
|---------------------------|----------------|---------------|
| 20411                     | 3057           | 511           |

The pine needles were distributed uniformly on the table in order to obtain homogenous fuel beds of 1 m width and 2 m long that occupy only the central part of the table. Different fuel loads (w) were tested: 0.6, 0.9 and 1.2 kg/m² that correspond respectively to fuel beds height of 3, 5 and 7 cm. The experiments were conducted either with no slope or with a table inclination equal to 20°. For each configuration, at least four repetitions were carried out.

The fires were ignited along the entire width of the fuel bed by using between 3 and 6 mL of alcohol. The rate of spread was calculated from the elapsed time of the flame front to cover intervals of 0.25 m along the bench. Thus, eight data points were obtained for each experiment and a least-squares regression was used to fit a straight line to the data points in order to obtain the rate of spread (ROS). Flame length (L_f), flame height (H) and flame angle (β) were determined from photographs taken by a camera located perpendicularly to the fire spread direction. The camera was automatically
controlled to take pictures every 2 to 4 seconds, depending on the rate of spread of the fire. For each experience, from 30 to 50 images were analyzed to compute the flame length, flame height and flame angle. Figure 2 shows how these variables were measured since, as pointed out by Anderson et al. [18], flame geometry descriptors are not univocally described on the literature. Flame length and flame height were expressed following the suggestions of [18]. Nevertheless, flame length and height were measured from the top of the fuel bed due to restrictions on the images processing.

\[ C_{4.15}H_{6.65}O_{2.51} + 4.56(O_2 + 3.76N_2) \rightarrow 4.15CO_2 + \frac{6.65}{2}H_2O + 17.14N_2 \]  

(1)

The calculations were performed by using simplifying assumptions. The main ones are listed below. The amount of energy released by complete combustion per unit mass of oxygen consumed is taken constant. All gases are considered to behave as ideal gases. The analyzed air is defined by its composition in O\(_2\), CO\(_2\), H\(_2\)O and N\(_2\). All other gases are lumped into N\(_2\). The heat release rate is given by the oxygen molar flow rate:

\[ HRR = E \left( \dot{n}_{O_2}^o - \dot{n}_{O_2}^e \right) W_{O_2} \]  

(2)

where \(\dot{n}_{O_2}^o\) and \(\dot{n}_{O_2}^e\) represent respectively the molar flow rates of O\(_2\) in incoming air and in the exhaust duct and \(W_{O_2}\) is the molecular weight of oxygen. The volume flow rate of incoming air, referred to standard conditions is:

\[ V_a = \frac{\dot{n}_{O_2}^o W_{air}}{X_{O_2}^o \rho_0} \]  

(3)

where \(X_{O_2}^o\) is the molar fraction of O\(_2\) in incoming air and \(W_{air}\) is the molecular weight of dry air at 25 °C and 1 atm. The oxygen depletion factor is introduced for convenience. It is given by:
Combining Eq. (2)-(4), one obtains:

$$\phi = \frac{\dot{n}_{O_2} - \dot{n}_{O_2}^*}{\dot{n}_{O_2}}$$

(4)

Gases are measured on a dry basis since the analyzers cannot handle wet mixtures. Thus, the mole fraction of gases in air is derived from the analyzers’ measurement and from air humidity. For instance, the mole fraction of oxygen in air is given by:

$$X_{O_2} = (1 - X_{H_2O}) X_{O_2}^a$$

(6)

Where superscript $a$ denotes the mole fraction in the analyzers. Unfortunately, in an open system, not the incoming air flow rate $\dot{V}_a$ but the flow rate in the exhaust duct $\dot{V}_s$ is measured. A relationship between $\dot{V}_a$ and $\dot{V}_s$ is obtained and after some development [19], the HRR is given by the three following relations:

$$HRR = \frac{E \rho_0 W_{O_2}}{W_{air}} X_{O_2}^* \phi \dot{V}_a$$

(5)

$$\dot{V}_{s,298} = 22.4 A \frac{k_t}{k_p} \frac{\Delta P}{T_s}$$

(8)

$$\phi = \frac{X_{O_2}^a (1 - X_{CO_2}^a) - X_{CO_2}^a (1 - X_{CO_2}^e)}{X_{O_2}^a (1 - X_{CO_2} - X_{O_2})}$$

(9)

where $X$ denotes the molar fraction and $\rho_0$ is the density of dry air at 298K and 1 atm. $\dot{V}_{s,298}$ is the standard flow rate in the exhaust duct. $\alpha$ is the expansion factor for the fraction of the air that was depleted of its oxygen. The superscript $^*$ is for the incoming air. A is the cross sectional area of the duct, $k_t$ is a constant determined via a propane burner calibration, $k_p=1.108$ for a bi-directional probe, $\Delta P$ is the pressure drop across the bi-directional probe and $T_s$ is the gas temperature in the duct. The HRR is therefore computed from many variables and each variable has a corresponding uncertainty. In this study, the instrumentation is similar to that of the Room Corner Test [20], for which Axelsson et al. [21] have analyzed the uncertainty considering individual sources of errors for rate of heat release measurements. The combined expanded uncertainty was provided with a coverage factor of 2, giving a confidence level of 95%. The oxygen concentration measurement, the mass flow rate measurement and the heat of combustion factor $E$ were identified as the major sources of uncertainty. In our study, the measurements of oxygen concentration and of mass flow rate were calibrated. The uncertainty due to the heat of combustion factor was reduced by estimating its value with the following expression:

$$E = \frac{\Delta H_{c,net}}{n_{O_2} W_{fuel}} = 13.98 \text{ MJ/kg}$$

(10)

where $n_{O_2} = 4.56$ (Eq. (1)) and $W_{fuel}$ is the molecular weight of the fuel. This value corresponds to an increase of 6.7 % compared to Huggett’s constant (13.1 MJ/kg).
3. Results and discussion

3.1. Geometry of the flame front
The geometry of the flame front was influenced by the slope and the fuel load. For experiments without slope, the flame front exhibited a nearly linear shape (Fig. 3a). On the edges of the bed, the flame front was however slightly curved and the flame height was lower than in the centre. For experiments under a slope of 20°, the flame front had a V-shape (Fig. 3b). The fire head was located approximately in the middle of the fuel bed. The V angle tended to decrease when the fuel load was increased. These observations are coherent with those of [13].

Figure 3. Picture of the flame front a) under no-slope condition b) under 20° up slope condition.

Figure 4 presents the flame lengths and heights for the different configurations. For a given fuel load, the flames were higher for the experiments with a slope. These observations are consistent with literature results [9-11]. The increase coefficient was of the order of 1.4. For experiments without slope, length and flame height had similar values because the flame had a low inclination. For propagation under slope condition, the flame lengths and heights changed significantly as the angle of inclination was greater (about 28°) [11]. The flame was also influenced by the fuel load. The lengths of the flame and of the flame front increase with increasing fuel load.

Figure 4. Flame length and flame height. Error bars correspond to the flame lengths.

3.2. Rate of spread
Figure 5 shows the mean position of the flame front for the different experiments. The flame front propagated with a nearly constant speed and a steady rate of spread was reached whatever the fire front shape. For a same fuel load, the rate of spread was about 2.7 times higher for experiments with slope that without slope [11-13]. The rate of spread also increased with fuel load [9]. When the fuel load was multiplied by 1.5 and 2, mean ROS were multiplied by 1.35 and 1.53 for experiments
without slope and by 1.68 and 1.59 with the slope of 20°. For a table inclination equal to 20° and with a fuel bed of 1 m width and 2 m long, the rate of spread seems to tend towards a maximum value close to 16 mm/s; this asymptotic threshold is linked to the scale of the combustion table.

3.3. Mass loss rate (MLR) and heat release rate (HRR)

The temporal evolution of the mass of the fuel bed is given in Fig. 6. The mass loss corresponds to the thermal degradation of the pine needles, namely oxidative pyrolysis and char oxidation. Since the needles were oven dried before the tests, the mass loss due to dehydration was not significant. The mass loss rates (MLR) were influenced by both the slope and the fuel load. At 20°, the MLR were higher than without slope. Only experiments performed with a fuel load of 0.6 kg/m² had a constant mass loss rate (mean value equal to 5.95 g/s with a standard deviation (s.d.) of 0.78). For the others, an increase was observed during the fire spread. For experiments without slope, the MLR became almost constant after a time depending on the fuel load (between 25 and 60 s). The mean values were equal to 2.46 (s.d. 0.11), 4.51 (s.d. 0.82) and 8.06 g/s (s.d. 0.70) for 0.6, 0.9 and 1.2 kg/m² respectively. Under slope conditions, an increase of the MLR with time was measured due to the increase of the fire front curvature (from linear-shape to V-shape). When the fuel load increased from 0.6 kg/m² to 0.9 and 1.2 kg/m², the mean MLR were multiplied by 1.9 and 3.0.
Instantaneous heat release rates (HRR) measured during the fire tests are displayed in Fig. 7. For experiments performed without slope, a quasi-steady state was reached for all fuel loads. The average heat release rates were 44 (s.d. 4.6), 84 (s.d. 17) and 146 (s.d. 16) kW for 0.6, 0.9 and 1.2 kg/m², respectively. The greater the fuel load was, the higher the heat release rate was. The mean HRR were multiplied by 1.9 and 3.3 with the increasing of fuel load by a factor of 1.5 and 2. However, the flameout occurs earlier for higher fuel load (Fig. 6) due to the increase in the rate of spread (Fig. 5). For experiments with a slope of 20°, the quasi-steady state was only reached for a fuel load of 0.6 kg/m² (mean value equal to 103 (s.d. 15) kW). For the other experiments, the heat release rate continued to increase until the flame front reached the end of the table. At the flameout, the HRR reached about 296 (s.d. 48) kW and 382 (s.d. 14) kW for a fuel load of 0.9 and 1.2 kg/m² respectively. The increase of the HRR was due to the shape of the flame front. Initially, the flame front followed a straight line due to the ignition but it took gradually a V-shape. Thus, the fire front perimeter increased progressively and more fuel was consumed leading to an increase of the MLR (Fig. 6) and of the HRR (Fig. 7). For the experiments performed without slope or with a fuel load of 0.6 kg/m², the shape of the fire front was roughly conserved during the fire spread. Thus, the MLR (Fig. 6) and the HRR (Fig. 7) remained almost constant. The mass loss rate and the heat release rate are therefore correlated. Furthermore, these results confirm that the rate of spread is not the good descriptor to understand the dynamics of fire spread. The rate of spread can be constant during the propagation, whereas the MLR and HRR do not reach a steady state.

![Figure 7. Heat release rate versus time.](image)

3.4. Effective heat of combustion
The effective heat of combustion $H_{\text{eff}}$ is representative for real fire conditions where there is unlimited availability of air. A global (smoldering and flaming) effective heat of combustion was determined for each test, $i$, by dividing the total heat released by the total mass:

$$
H_{\text{eff}}^{i} = \int_{t_{i}}^{t_{f}} HRR \, dt \left( m_{in} - m_{fi} \right)
$$

where subscript $in$ and superscript $fi$ are for initial and final time. Then, for each fuel load, a mean effective heat of combustion $H_{\text{eff}}$ was calculated by averaging the global effective heat of combustion obtained for the set of tests. The combustion efficiency represents the ratio between the average effective heat of combustion and the heat yield:

$$
\chi_{\text{eff}} = \frac{H_{\text{eff}}}{H}
$$
H is the heat yields calculated from the net heat of combustion adapted to the moisture content of fuel ($\text{p}_M$):

$$H = \frac{\Delta H_{\text{c,net}}}{1 + \text{p}_M / 100}$$  \hspace{1cm} (13)

Both mean effective heat of combustion and combustion efficiency are provided in Table 2. The effective heat of combustion and the combustion efficiency did not appear to be dependent on either the fuel load or on the slope. The mean value for the effective heat of combustion was 17957 kJ/kg, what corresponds to a combustion efficiency of 0.932. These values are consistent with the measurements of Babrauskas [22] for flaming combustion of Douglas-fir. In a free burn test, the fuel is burned with unlimited access to air, but some of the volatiles (CO, soot and unburnt hydrocarbons) containing further potential energy does not burn completely.

**Table 2.** Effective heat of combustion (kJ/kg) and combustion efficiency in parenthesis

| Slope (°) | Fuel load (kg/m²) | Effective heat of combustion (kJ/kg) | Combustion efficiency |
|----------|------------------|-------------------------------------|-----------------------|
| 0        | 0.6              | 18008 (0.926)                       | 0.926                 |
|          | 0.9              | 18077 (0.930)                       | 0.930                 |
|          | 1.2              | 18086 (0.930)                       | 0.930                 |
| 20       | 0.6              | 17936 (0.923)                       | 0.923                 |
|          | 0.9              | 18122 (0.952)                       | 0.952                 |
|          | 1.2              | 17515 (0.929)                       | 0.929                 |

Thanks to the effective heat of combustion found previously, the heat release rate can be estimated from the mass loss rate (MLR) with:

$$\text{HRR (kW)} = H_{\text{eff}} \cdot \text{MLR} = 17957 \cdot \text{MLR}$$  \hspace{1cm} (14)

Figure 8 presents the measurements by OC calorimetry and the results obtained with Eq. 14 for various fuel loads and slopes. For all configurations, the two curves were close. The mean relative error was equal to 14.9 % and was mainly due to the fluctuations of the mass loss measurement. This approach provided therefore an accurate estimation of the HRR whatever the fuel load or the slope. In the absence of a cone calorimeter, the measurement of the MLR could be a good alternative method to estimate the heat release rate or fireline intensity.

**Figure 8.** Comparison between measured and estimated HRR for a) 0.6 kg/m² without slope b) 1.2 kg/m² with a slope of 20°

4. **Conclusion**

In this study, oxygen consumption calorimetry was used to analyze the spreading of fire across pine needles beds for various fuel loads, with or without slope. From these data, the influence of these two parameters was underlined. The main results can be summarized as follows:
• For experiments without slope and for 0.6 kg/m² with a 20° slope, the HRR and the MLR reach a quasi-steady state. For experiments at 20° slope with fuel loads of 0.9 and 1.2 kg/m², the HRR and the MLR increase during the spread. This is due to the increase of the length of the flame front.
• The only study of the rate of spread does not highlight this behaviour, since the ROS is constant during the propagation whatever the slope or the fuel load.
• The effective heat of combustion depends on neither the fuel load nor the slope. The mean value is equal to 17957 kJ/kg.
• The heat release can be accurately estimated with the mass loss rate and the effective heat of combustion.

References
[1] Mell WE, Jenkins MA, Gould J and Cheney P 2007 Int. J. Wildland Fire 16 1
[2] Morvan D, Meradji S and Accary G 2008 Fire Saf. J. 44 50
[3] Fiorucci P, Gaetani F and Minciardi R 2008 Environ. Model. Soft. 23 690
[4] Zhou X, Mahalingam S and Weise D 2007 Proc. Combust. Inst. 31 2547
[5] Balbi JH, Rossi JL, Marcelli T and Santoni PA 2007 Combust. Sci. Technol. 179 2511
[6] Rothermel RC 1972 A mathematical model for predicting fire spread in wildland fuels. U.S Department of Agriculture, Forest Service, Research Paper INT-115. Intermountain Forest and Range Experiment Station, Ogden, Utah.
[7] Wilson RA 1990 Reexamination of Rothemel's fire spread equations in no-wind and no-slope conditions U.S. Department of Agriculture, Forest Service, Research Paper INT-434 Intermountain Forest and Range Experiment Station, Ogden, Utah.
[8] Cheney NP, Gould JS and Catchpole WR 1993 Int. J. Wildland Fire 3(1) 31
[9] Dupuy JL 1995 Int. J. Wildland Fire 5(3) 153
[10] Van Wagner CE 1968 Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence Department of Forestry and Rural Development, Publication 1229, Ottawa
[11] Mendes-Lopes JM, Ventura JM and Amaral JM 2003 Int. J. Wildland Fire 12(1) 67
[12] Viegas D 2004 Int. J. Wildland Fire 13(2) 143
[13] Dupuy JL, Maréchal J, Portier D and Valette JC 2011 Int. J. Wildland Fire 20 272
[14] Barboni T, Morandini F, Rossi L, Molinier R, Santoni PA 2012 Combust. Sci. Technol. 184 186
[15] Babrauskas V, Peacock RD 1992 Fire Saf. J. 18 255
[16] Bartoli P, Simeoni A, Biteau H, Torero JL and Santoni PA 2011 Fire Saf. J. 46 27
[17] Moro C 2006 Détérmination des caractéristiques physiques de particules de quelques espèces forestières méditerranéennes, INRA PIF2006-06.
[18] Anderson W, Pastor E, Butler B, Catchpole E, Dupuy JL, Fernandes P, Guijarro M, Mendes-Lopes JM, Ventura J 2006 Evaluating models to estimate flame characteristics for free-burning fires using laboratory and field data Proc 5th International Conference on Forest Fire Research (Figueria da Foz, Portugal, 27-30 November 2006).
[19] Parker WJ 1982 Calculations of the heat release rate by oxygen consumption for various applications, NBSIR 81–2427–1.
[20] International Standard. Fire tests—full scale room test for surface products, ISO 9705. Geneva: International Organization for Standardization, 1993.
[21] Axelsson J, Andersson P, Lönnemark A, Van Hees P,Wetterlund I 2001 Uncertainties in measuring heat and smoke release rates in the Room/Corner test and the SBI, SP report 2001:04, Boras: Swedish National Testing and Research Institute.
[22] Babrauskas V 2002 The SFPE Handbook of Fire Protection Engineering (National Fire Protection Association and The Society of Fire Protection Engineers: M.A. Quincy, J.P. Di Nenno, W.D. Walton)