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Characteristics of surface litter fires: A systematic experimental study

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Abstract

This work presents the results of laboratory experiments, focused on the characterization of surface wildland fires propagating in a litter fuel bed. A series of fire tests are conducted using an inclinable combustion table, measuring 2 m x 2 m, aiming to identify the effects of several important operational parameters on the characteristics of the developing fire. The parameters studied are the slope angle and the fuel load. A broad sensor network is installed, including 52 thermocouples, 3 bi-directional velocity probes, 2 heat flux sensors, a weighing system, 2 optical cameras and a real-time gas analyser. The obtained measurements are used to determine the time evolution of several characteristic parameters, such as position of the flame front (that yields the mean rate of spread), heat release rate, heat flux, axial velocity, as well as the mass loss. The construction of a 2D temperature field from the thermocouples that rest on a plane parallel to the propagation axis, illustrates several interesting flame characteristics. It is found that the rate of spread increases with slope angle and fuel load, whereas the heat release rate increases with slope and, dramatically, with fuel load.

1. Introduction

Wildland fires draw a large attention from multiple fields of science and engineering, due to the broad range of interacting physical and chemical phenomena that develop in multiple temporal and spatial scales. Understanding the wildland fire behaviour aims in acquiring in-depth scientific knowledge that will enable to adequately predict several key characteristics, such as flame rate of spread. The main parameters affecting the behaviour of wildland fires are the characteristics of the flora fuel, the atmospheric conditions, and the local topography.

Laboratory experimentation on wildland fires is broadly used to investigate various aspects of their characteristic behaviour (Rothermel and Anderson, 1966; Viegas and Pita, 2004). Although laboratory-scale experiments cannot incorporate the full spectrum of length scales observed in real-scale wildland fires, they still offer some significant advantages, since they facilitate controllability, repeatability and instrumentation management. In this context, small-scale fire tests may provide significant insight to the spread rate of surface wildland fires, thus providing valuable information to further understand and analyse more complicated wildland fire scenarios, e.g., crown fires (Scott et al., 2014).

A broad range of physical quantities has been proposed to describe the behaviour of a wildland fire. Undoubtedly, the most widely studied quantity, of both academic and practical value, is the Rate of Spread (ROS); knowledge of a wildland fire's spatio-temporal evolution is required to effectively coordinate fire suppression and civilian evacuation activities. In terms of the fire's combustion characteristics, the Heat Release Rate (HRR) is the most common quantity used to describe the thermal power and, thus, the severity of the fire; estimation of the HRR is usually performed in a laboratory environment by means of the oxygen consumption calorimetry method.Other measured quantities like the fuel mass loss rate, the radiative heat flux and the temperatures inside and above the fuel bed, can potentially reveal significant information regarding the underlying phenomena (e.g. convection, radiation) that affect the fire behaviour. .

In this work, a series of surface (litter) fire tests are performed on an inclinable combustion table, aiming to investigate the impact of several operational parameters on certain significant quantities that describe the fire behaviour. The investigated parameters are the fuel bed slope and the fuel load, and the measured properties are the mean Rate Of Spread (ROS), the Heat Release Rate (HRR), the mass loss rate, the heat flux, the axial velocity profile as well as the temperature spatial distribution, above and "inside" the fuel bed.

2. Experimental apparatus and experimental method

The experimental apparatus used is an inclinable combustion table, where fuel beds of Pinus Halepensis needles are evenly distributed. The table has an area of 2 m x 2 m and it can change its slope angle from 0 to 30 degrees (c.f. Figure 1). The table is located under an exhaust hood, which is used to collect the combustion product gases; a continuous gas analyser is employed to estimate the instantaneous HRR, using the oxygen consumption calorimetry method (Thornton, 1917; Janssen, 1991). The combustion table is equipped with a broad network of measuring instruments, i.e., a grid of 52 thermocouples distributed on a vertical plane along the direction of fire spread, near the middle of the fuel bed's width (y = 40 mm); 3 bi-directional velocity probes and 2 heat flux meters (one located vertically, at the downstream end, and the other located horizontally, at the level of the fuel bed surface) are also installed. To measure mass loss, the inclinable table rests upon three load cells. The positions of the instruments on the table are presented in Figure 2.

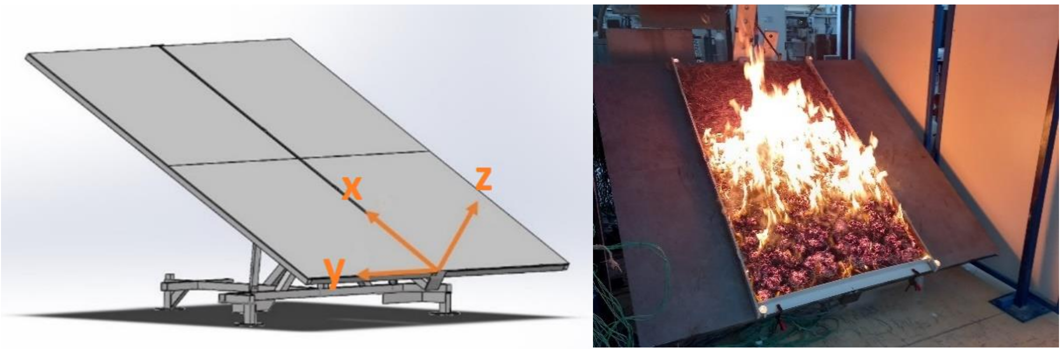

Figure 1: Model representation of the combustion table and its coordinate system (left) and indicative view of the experimental apparatus during a fire test (right).

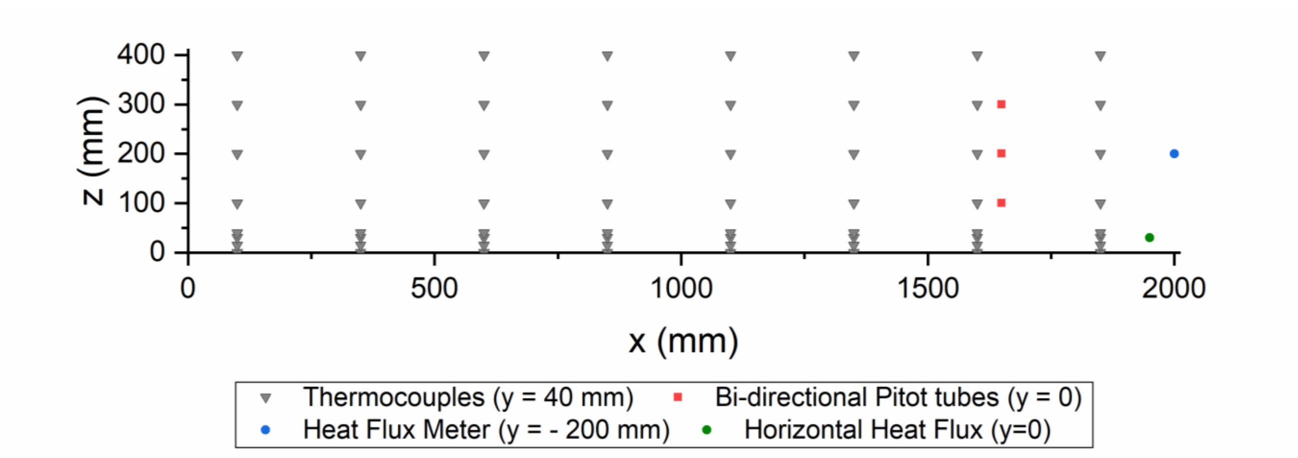

Figure 2: Locations of the measurment sensors (the coordinate system is defined in Figure 1).

The performed parametric study investigated the impact of two operational parameters, which are known to affect the characteristics of the developing fire, i.e., the fuel load and the slope angle. The specific characteristics of the 5 experimental test cases are presented in Table 1. For all the fire tests conducted, the fuel bed dimensions were 1.0 m (width) x 1.9 m (length). The Fuel Moisture Content was measured with a moisture analyser, yielding for all the experiment a value around 9% (in dry basis). The fire was linearly ignited at the upstream edge of the fuel bed (x = 50 mm) with the help of a paper string soaked in ethanol. Each test case was repeated 3 times; the presented results are averaged values.

Table 1- Characteristic parameters, and results of the 5 investigated test cases.

Test case	Slope angle, S (deg)	Fuel load (wet basis), m'' (kg/m^2)	Fuel bed height, δ (mm)	Rate of Spread, R (mm/s)	Fire duration, t_{end} (s)	Peak HRR, HRR_{max} (kW)
S00-M0_50	0	0.50	30	3.7	515	31
S00-M0_25	0	0.25	15	3.0	627	17
S20-M0_50	20	0.50	30	9.8	194	69
S30-M0_50	30	0.50	30	40	48	205
S00-M0_25	30	0.25	15	36	53	126

The ROS was estimated using temperature measurements from thermocouples located at the top surface of the fuel bed. More specifically, the first time that the second derivative of the temporal temperature recording was zero was assumed to be the time that the flame front reached that specific thermocouple. The rate of spread, R (mm/s), was estimated via linear interpolation of the resulting points of time and x position for the eight thermocouples in the array. The time the fire front required to reach the end of the fuel bed, t_{end} (s), was calculated by dividing the length of the fuel bed with the respective R; this value was used in each test case to define a dimensionless "flame propagation time", $\tau = t / t_{end}$, which is used in subsequent plots, allowing better comparison of the temporal evolution of the measured properties.

3. Results and Discussion

The temporal evolution of the flame front position is presented in Figure 3; the respective mean ROS values are given in Table 1. The ROS is found to increase with increasing slope as well as with increasing fuel load, in agreement with the existing literature (e.g. Tihay et al., 2014; Campbell-Lochrie et al., 2020). It is interesting to note that for the cases of 30º slope, there is a rapid increase of ROS. For all test cases, the instantaneous R appears to be relatively constant, thus suggesting the establishment of "steady-state" fire spreading conditions.

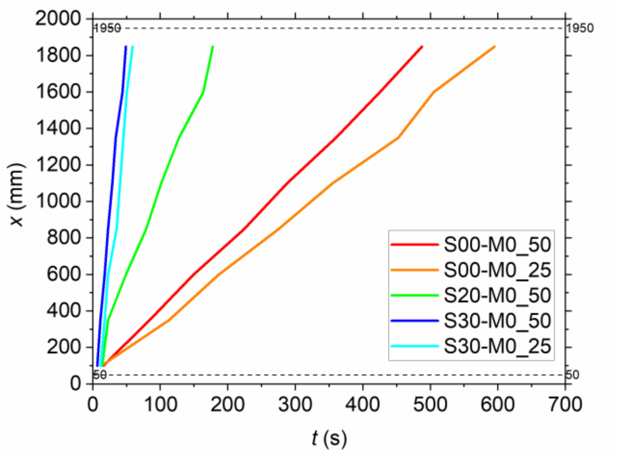

Figure 3 – Estimated temporal evolution of the flame front position.

The temporal evolution of the estimated HRR and the dimensionless mass loss are illustrated in Figure 4. Regarding the HRR (Figure 4, left), a similar trend to the temporal evolution of ROS is observed; more specifically, the HRR is found to increase with increasing slope and fuel load (Tihay et al., 2014). The effect of fuel loading seems to be stronger for the HRR, compared to that observed for the ROS, which is not surprising, since an increase in the fuel load results in a corresponding increase in the total amount of energy available for combustion. As far as the HRR temporal profile is concerned, it appears to reach a prolonged "plateau", for the test cases where the slope was less than 30 degrees. On the contrary, for the S30 test cases, the HRR exhibited a dramatic increase, showing a rather instantaneous "peak" before decreasing again. For all test cases, the HRR started to decrease roughly at $\tau = 1$. From that point on, it seems that the higher the peak value (HRR_{max}, c.f. Table 1), the longer the combustion processes continued to evolve behind the flame front. The continuation of the combustion process after $\tau = 1$ is also evident by the temporal evolution of the dimensionless mass loss

(Figure 4, right), where the mass continues to decrease for test cases S20 and S30, whereas it essentially ceases for test cases S00. Additionally, it is noted that with increasing the slope and the fuel load (while keeping the bulk density, $\rho_b = m''/\delta$, constant) the remaining fuel mass increases. This is mainly owed to the non optimal ventilation of the lower part of the fuel bed when its depth is increased as a consequence of the fuel load increase; in addition, the high ROS values observed with increasing slope, lead to reduced flame front residence times over the fuel bed, thus resulting in a prolonged combustion process.

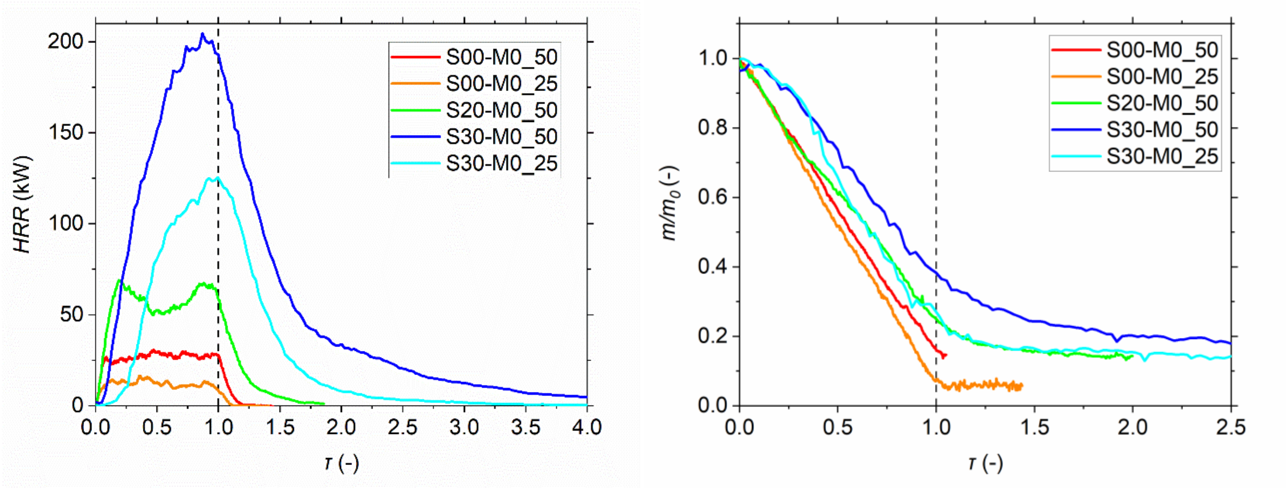

Figure 4 – HRR (left) and "normalised" mass loss (right) as a function of dimensionless time, τ.

The developing temperature fields above and inside (the dashed line corresponds to the fuel bed thickness, δ), the fuel bed, at three characteristic dimensionless times (0.25, 0.50 and 0.75) are presented in Figure 5 for all test cases. Increasing the slope results in a general increase of the temperature of the flame front, in agreement with relevant observations in the literature (Morandini et al., 2001); the same trend is observed when the fuel load is increased. The inclination angle of the flame toward the plane of propagation is increased with increasing slope angle. In addition, as the slope angle increases the flame front "depth" increases as well.

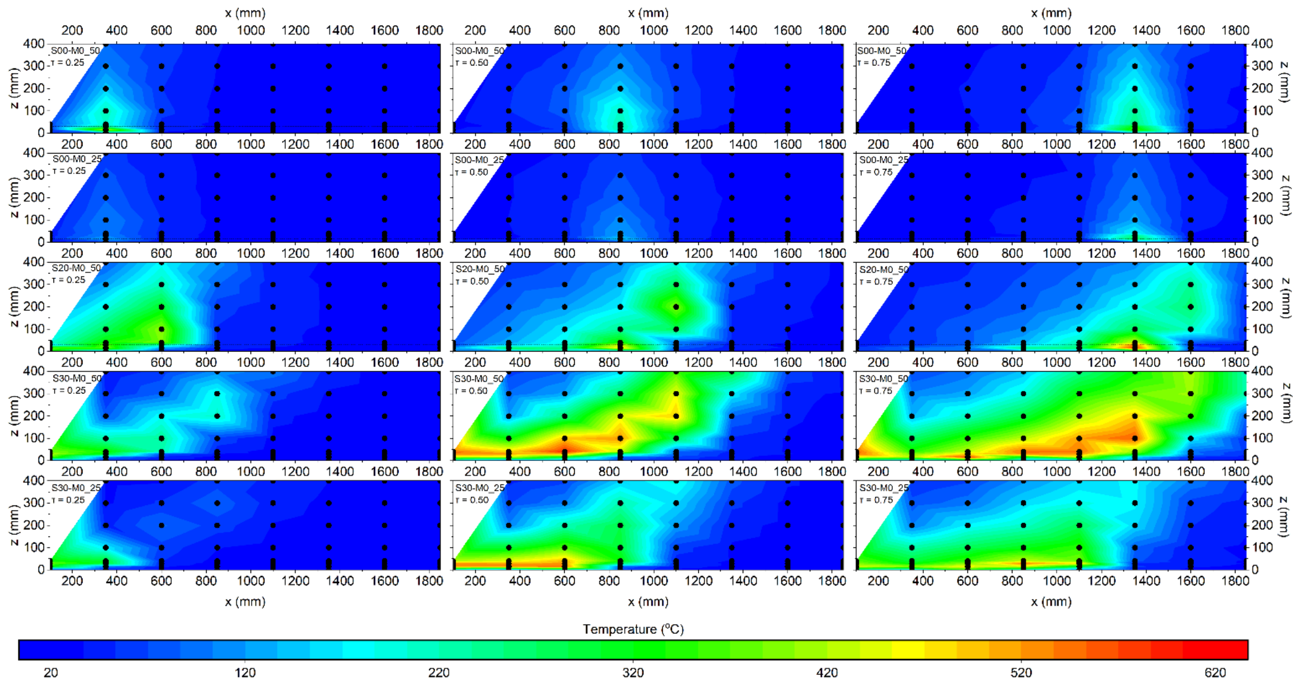

Figure 5 - Temperature contour plots for all test cases, at three characteristic dimensionless time values.

The temporal evolution of the horizontal heat flux at the downstream end of the fuel bed is presented in Figure 6. Again, increasing the slope and the fuel load result in an increase of the heat flux from the flame front. This is due to the fact that increasing the fuel load results in an increase of the flame height, while increasing the slope decreases the flame tilt angle (the angle between the flame front and the combustion table). Both trends results in an increase of the radiative view factor which enhances the measured radiative heat flux. The latter is additionally enhanced by increased temperatures (as a result of increasing fuel load), as well as by increased emissivity (due to the increase of the flame depth).

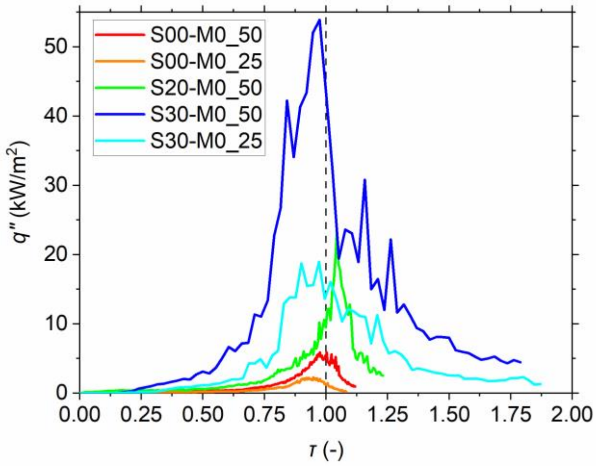

Figure 6: Temporal evolution of horizontal heat flux at the downstream end of the fuel bed.

The temporal evolution of the axial velocities near the downstream end of the fuel bed (*x* = 1650 mm) at three different heights (z = 100, 200 and 300 mm) are presented in Figure 7. At the height of 100 mm, close to the fuel bed surface, the negative velocities prior to the flame front's arrival indicate a downstream entrainment of air. After the passing of the flame front the axial velocities turn positive with a trend to increase with increasing slope. The magnitude of that upstream velocity seems to be unaffected by the fuel load (test cases M0_50 and M0_25), in contrast to the downstream velocity. At higher levels (200 mm and 300 mm), downstream air entrainment appears mainly in the non-sloped test cases (S00); additionally, the effect of fuel load seems to be stronger for test cases S30. As expected, the axial velocity magnitude decreases with increasing height.

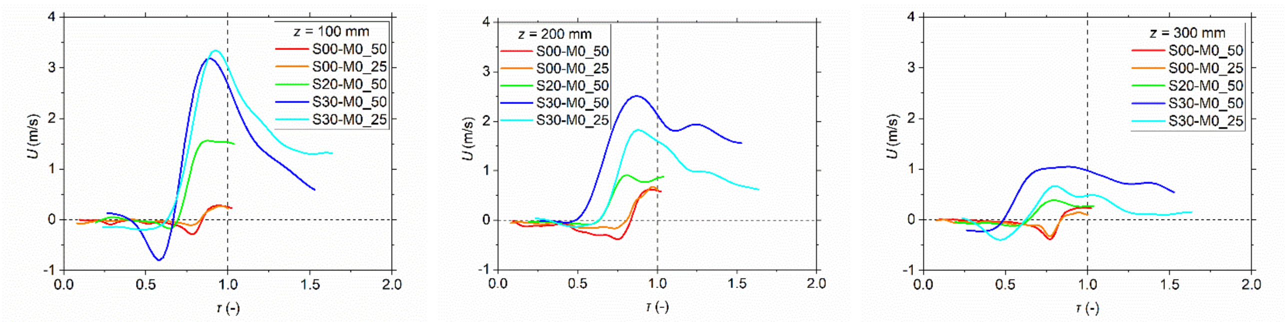

Figure 7: Axial velocity measurements at z = 100 mm (left), 200 mm (middle) and 300 mm (right).

4. Concluding Remarks

A parametric investigation regarding the effects of slope angle and fuel load on the characteristics of surface wildland fires has been conducted on a laboratory-scale combustion table. The trends observed are generally in agreement with respective findings reported in the literature. ROS increases with increasing slope angle and fuel load; a rapid increase is observed for a 30° slope angle. HRR follows a similar trend; the fuel load has a stronger influence on HRR compared to ROS. After ignition, the HRR seems to reach a plateau for all test cases, except those with a 30° slope, where HRR exhibits a continuous increase until a peak value is reached and then a gradual decrease. The remaining fuel mass increases with increasing slope, due to the appearance of incomplete combustion conditions at the lower parts of the fuel bed. The spatio-temporal evolution of gas temperatures reveals that the flame depth increases with increasing slope and fuel load, while the flame tilt angle is decreased. Moreover, increasing fuel load and slope result in increased flame front temperatures; the same observations appears to be true also for the heat flux. Finally, axial velocity measurements reveal the magnitude and the direction of the upstream and downstream air entrainment flows and how they change with slope and fuel load.

5. References

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