Experimental and numerical investigation of shrub combustion

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ABSTRACT

The use of physics-based models to simulate vegetation fires has been steadily increasing over the last decade. These models offer the possibility to study quickly and at a low cost the combustion of vegetation according to a wide set of parameters which are difficult to control experimentally. However, the validation and improvement of these models is still ongoing and coupled experimental / numerical approaches are needed.

In a previous work, a validation of the numerical code WFDS was done for the spreading of fires across pine needles fuel beds. It highlighted the ability of WFDS to reproduce the combustion dynamics and the related physical quantities (heat release rate, mass loss rate, rate of spread) during the growing and steady-state phases of the fire. The objective of the present work is to test WFDS for the prediction of the combustion of a natural shrub, which is a more complex fuel than a fuel bed. As a first step, 3 shrubs of rockroses (Cistus monspeliensis) were characterized. The distribution of the different classes of particles that compose the shrubs was determined and used as input for the shrub model. A series of 41 fire tests were conducted on the shrubs to investigate their flammability. Ignition was performed using radiant panel. The measurements of the main physical quantities were also used as a comparison basis for the numerical approach. A numerical model of shrub was developed from the characterization results. Then, the combustion of the shrub was simulated with WFDS. The grid mesh resolution needed for the simulation was estimated from the extinction length within the shrub crown and from the heat release rate (HRR) during the fire tests. Finally, experimental measurements and predictions were compared to determine the capability of WFDS to reproduce the combustion of the shrubs.

The experimental investigation of the shrub flammability showed four different regimes of combustion governed mainly by the location of ignition. Simulations were run for the flammability regime that exhibits the best reproducibility. The comparison between simulation and experimental results demonstrated a good ability of WFDS to assess the most relevant fire properties, namely the peak of HRR, flame duration and consumption rate. The main differences between the predictions and observations were identified during the ignition and extinction phases. A plateau of HRR is predicted shortly after the ignition, limiting the fire growth. In addition, the duration of the predicted smoldering phase is too short which causes a total extinction of the fire few seconds after the end of the flaming phase.

KEYWORDS: Flammability, Shrub combustion, Fire behavior
INTRODUCTION

Continuous efforts are being made towards the understanding of the spread of wildfires which increasingly threaten ecosystems, houses and people. The improvement of the computational resources and the ability of the physics-based models to predict the intricate processes involved in combustion, has led to an increase in the use of numerical approaches to study these fires. However, the development of these models is still pending and they need to be compared over a wide range of configurations in order to be improved. The validation tests are commonly performed across simple fuel structure, mainly fuel bed (needles) or grass consisting of a single type of particles.

In particular, the Wildland-urban interface Fire Dynamics Simulator (WFDS) was tested at field scale with large experimental grassland fires [1]. However, this first modelling approach considered a boundary fuel model. A first improvement of WFDS [2] has rendered the model capable of representing the spatial distribution of different fuel elements (leaves, twigs) within the vegetation. The char oxidation was nevertheless not considered at this stage. Then a modification of the thermal degradation model was done in order to include the char combustion processes and refine the gasification law [3]. In this work WFDS was validated for fire spreading across beds of pine needles.

In order to extend the testing of WFDS, the present study aims to investigate the combustion of a more complex living vegetation. Shrubs of rockroses were considered, which are highly porous media composed of different classes of particles with different thickness and moisture contents. The vegetation samples were characterized to obtain the mass proportion of the different classes of particle sizes as well as their spatial distribution. These results were used to develop a numerical model of a typical shrub of rockrose. Then, experiments were done in order to assess their flammability and to collect data on the most relevant physical quantities to test WFDS.

Different burning behaviors depending on the ignition location, time to ignition and vegetation mass distribution, were put to the fore. They were classified into four distinct types of flammability. The simulations were done for one of the identified flammability group.

CHARACTERIZATION OF THE SHRUB STRUCTURE

A good knowledge of the structure and mass distribution of the different classes of particles within the shrubs of rockrose is necessary to accurately predict their combustion with WFDS. Therefore, a characterization of 3 shrubs with similar size was performed. Their average height and crown diameter were 1.23 and 0.68 m, respectively. The shrubs were placed inside a 1.45 m high, 0.9 m long and 0.9 m wide cubic metallic mesh structure allowing the destructive sampling of the vegetation (252 cubes of 0.15 m side). The shrubs were cut off following the pattern of this grid. The particles in each sampling cube were then oven dried and separated following their thickness (leaves, dead twigs with 0-2 mm diameter, live twigs with 0-2 mm, 2-4 mm, 4-6 mm and 6-25 mm diameters, respectively). The dry mass of each particle class was measured. It should be pointed out that the bases of the shrubs (up to 0.25 m height) were not considered in this characterization since they were composed of roots and large particles (diameter greater than 25 mm) expected not to participate in the early combustion processes, for the fire intensities considered in the present study. The mass proportion of each particle class is denoted by:

\[
\Gamma_k = \frac{m_{kd}}{m_d} \quad (1)
\]

where \(\Gamma_k\) is the mass fraction of particle class \(k\) in the shrub, \(m_{kd}\) represents the dry mass of the particle class \(k\) and \(m_d\) is the total dry mass of the shrub. A similar mass distribution was measured for the 3 shrubs of rockrose. Low standard deviations were obtained for all particle classes. Experimental results exhibit that a shrub of rockrose is composed of 22.1 ± 0.8 % of leaves, 5.4 ± 0.8 % and 20.8 ± 1.3 % of dead and live twigs with a diameter between 0 and 2 mm respectively, 18.3 ± 0.9 % of live twigs with 2-4 mm diameter, 16.4 ± 1.6 % of live twigs with 4-6 mm diameter and 17.0 ± 4.0 % of live branches with 6-25 mm diameter. The shrub of rockrose is thus made of 48.3 ± 2.9 % of particle classes participating actively to the combustion [4].

The spatial distribution of the different classes of particles was determined following the height of the shrub, \(z\). The mass distribution function is defined as:

\[
\zeta_{kd}(z) = \frac{m_{kd}(z)}{m_d(z)} \quad (2)
\]
where \( m_{kd}(z) \) is the dry mass of the particle class \( k \) ranging between \( z - \frac{\delta}{2} \) and \( z + \frac{\delta}{2} (\delta = 15 \text{ cm}) \) and \
\[
    m_d(z) = \sum_k m_{kd}(z).
\]

Three parts were identified in the shrub according to the height: the base (from 0.27 to 0.59 m high), the intermediate zone (from 0.59 to 0.91 m high) and the crown (from 0.91 to 1.23 m high). It was observed that 78% of the mass of the leaves is in the crown. The particle class with 0-2 mm diameter is present at 82% in the crown and in the upper half of the intermediate part. For the 2-4 mm diameter class, we observed that 58% of their mass is in the intermediate part of the shrub. The rest of the 2-4 mm family was distributed almost identically in the other two parts of the shrub. Particles of the 4-6 mm diameter class are mainly present in the lower half of the intermediate part (37% of the mass of these particles) and in the base (46% of the mass of these particles). Finally, 95% of the total mass of the class 6-25 mm is located in the base.

**STUDY OF THE SHRUB COMBUSTION**

The fire experiments were carried out under a Large-Scale Heat Release apparatus (LSHR) (Figure 1). This device allows the measurement of the HRR over time (sampling rate 1 Hz). The shrubs were placed on a load cell. The smoke was extracted through a 3 m × 3 m hood with a volume flow rate of 1 m³/s. Two sets of two radiant panels, placed perpendicularly from each other to maximize the emitted heat flux, were used to preheat and ignite the shrub of rockroses. The radiant panels were heated at a temperature of 520°C which led to a radiant heat flux density of 20 kW/m². 41 fire tests were conducted and 29 were retained for the analysis. The shrubs had an average height of 1.25 m, a crown base height of 0.95 m and a crown diameter between 0.6 and 0.8 m. Their average mass was around 2 kg (including base). The shrubs were conditioned indoor at ambient temperature and humidity (25°C and 50%) for a period of 48 hours in order to obtain the expected range of moisture content (3-20 % for the leaves). The time to ignition was noted for each experiment. The flame duration and the rate of consumption of the fuel were also measured.

In order to study the flammability of the shrub four criteria were used namely ignitability, combustibility, sustainability and consummability. Then a Principal Component Analysis was done with these criteria and revealed the presence of four flammability regimes mainly dependant on the ignition position, mass distribution and time to ignition. An ignition zone in the higher part of the crown led to a weak or a moderate flammability. An ignition in the lower part of the shrub led to a high and fast flammability or to a high flammability with strong consumption of mass. As an example, the high and fast flammability regime presents a fast growing after the ignition with a HRR peak of 228 ± 15 kW and a flame duration of 44 ± 9 s. The rate of consumption of the shrubs was 25 ± 6 % which represents a crown consumption in the range of 57 - 97 %.

The measurements of the HRR over time for the different tests exhibited a good repeatability during the phases of fire growth and flaming combustion but they showed a greater variability for the extinction phase. Indeed, the ignition of large diameter (4-6 mm) particles sometimes occurred increasing the duration of the extinction phase without impact on the peak HRR and growth time.

![Figure 1: Layout of the experimental set-up, a) side view b) top view](image)
SIMULATION METHOD

Overview of WFDS

WFDS is a physics-based model of fire spread which purpose is to represent the fine mechanisms governing the fluid mechanics, the combustion and the heat transfers. [2]. The thermal degradation model was modified and coupled to the gas phase equations of heat and mass transfer. This degradation model is based on Arrhenius laws for the desiccation, pyrolysis and char oxidation [5]. Thus, the predicted HRR over time is the sum of the heat released by the flame (gas phase) and the HRR due to the char oxidation (solid phase). The modified degradation laws are:

\[ R_{H_2O} = \rho_{b,H_2O}A_{H_2O}T^{-1.2} a_{H_2O} \frac{e^{\frac{q_{H_2O}}{T_k}}}{T_k} \]  \hspace{1cm} (3)

\[ R_{pyr} = \rho_{b,pyr}A_{pyr} \frac{e^{\frac{q_{pyr}}{T_k}}}{T_k} \]  \hspace{1cm} (4)

\[ R_{char} = \frac{\alpha_{char} A_{char \rho} Y_{o2} \sigma_k \beta_k}{\sqrt{1 + \beta_{char}}} e^{\frac{q_{char}}{T_k}} \]  \hspace{1cm} (5)

where \( R_{k} \) represents the Reynolds number, \( R_{k} = 2 \rho_{k} u \nu / \mu \) with \( \nu = \frac{2}{\sigma_k} \), \( \sigma_k \) and \( \beta_k \) are the surface to volume ratio and compactness of the class \( k \) of particles, respectively. The equation governing the temperature of the fine particles, \( T_{k} \), was also modified as follow:

\[ \rho_{b,k} c_p \frac{dT}{dt} = - \Delta h_{vap} R_{H_2O} - \Delta h_{pyr} R_{pyr} - \alpha_{char} \Delta h_{char} R_{char} - \left( q_{c,p} \right)_{yb} - \left( \nabla \cdot q_{r} \right)_{yb} \]  \hspace{1cm} (6)

where the three first terms of the right-hand-side represent the desiccation (endothermic), the pyrolysis (endothermic) and the char oxidation (exothermic), respectively. The fuel element bulk contributions of convective and radiative heat transfer are represented by the fourth and fifth terms, respectively. The heats of vaporization, pyrolysis and char oxidation are \( \Delta h_{vap} = 2.259 \times 10^3 \, kJ \, kg^{-1} \), \( \Delta h_{pyr} = 418 \, kJ \, kg^{-1} \) and \( \Delta h_{char} = -32 \times 10^3 \, kJ \, kg^{-1} \), respectively [6]. The dimensionless parameter \( \alpha_{char} \) is the fraction of the heat generated by the char oxidation which is absorbed by the solid fuel and \( (1 - \alpha_{char}) \) by the gaseous phase. In this case and in other studies, it is considered empirically that \( \alpha_{char} = 0.5 \) [5]. Further details on the WFDS and the modifications done are in Perez-Ramirez et al. [3].

Shrub model

The mass distribution obtained during the characterization provided reliable data for the modeling of the shrub of rockrose. However, the Cartesian metallic mesh structure used did not match perfectly with the shrubs envelope. As a result, an underestimation of the bulk density occurs on their edges. Thus, a more realistic model composed of 6 frustums of 15 cm height was used. These frustums were chosen to match at best as possible with the average height and diameter along height of the shrub. WFDS allows the use of several classes of particles. Thus, the numerical shrub was modeled as the superposition of six fuel layers, each composed of one class of particles identified in the previous section. Finally, the bulk density \( \rho_{bk} \) of each particle class (Table 1)

\[ \rho_{bk}(z) = \frac{m_{kg}(z)}{V(z)} \]  \hspace{1cm} (7)

Concerning the vegetation, the surface-to-volume ratio for the leaves, the 0-2 mm, 2-4 mm, 4-6 mm and 6-25 mm classes were 2081, 1733, 1000, 666 and 400 m⁻¹, respectively. The density of the particles was 478 and 961 kg.m⁻³ for the leaves and the twigs, respectively. The mass fraction of consumed fuel turned into char and ashes was 30 % [7] and 13%. Finally, the radiative fraction (27 %) was estimated with the method detailed in[8]. The other model inputs (\( A_{pyr} = 36300 \, s^{-1} \), \( E_{pyr} = 7250 \, K \)) previously used [3] were kept in the present study.
Mesh resolution within the shrub and the reacting flow

The grid resolution needed to perform the simulations was estimated from two characteristic length scales associated with two physical phenomena involved in the combustion. The first length scale corresponds to the extinction length, \( \delta_R \), which represents the absorption of radiation by vegetation. \( \delta_R \) is given by:

\[
\delta_R = \frac{4}{\rho_v \sigma_v}
\]

(8)

The grid size used within the shrub, \( dx_b \), must be lower than \( \delta_R \). In this regard Mell et al. [3] proposed to use at most a grid cell size three times lower that \( \delta_R \) \((dx_b, \delta_R/3) \). A grid cell size five times lower than \( \delta_R \) \((dx_b, \delta_R/5) \) is also recommended. The second characteristic length scale allows to determine the grid size in the flow field for the buoyant plume and the flame regions. The grid resolution \( dx \) is given by the dimensionless expression \( z_c/d_x \) proposed by McGrattan et al. [9] where \( z_c \) represents the characteristic fire diameter. \( z_c \) depends on the fire HRR, \( q \), the density \( \rho_o \), specific heat \( c_p \), ambient temperature \( T_o \) and acceleration of gravity \( g \):

\[
z_c = \left( \frac{q}{\rho_o c_p T_o \sqrt{g}} \right)^{\frac{2}{5}}
\]

(9)

McGrattan et al. [4] suggested to choose a ratio \( z_c/d_x \) in the range of 4-16. The extinction length was calculated from the numerical shrub characteristics. A value of 0.144 m was obtained for \( \delta_R \) which corresponds to a grid size lower than 0.048 m and 0.029 m for \( dx_b, \delta_R/3 \) and \( dx_b, \delta_R/5 \), respectively. Concerning the flow computation in flame and buoyant plume regions, the mesh size was calculated from the HRR peaks obtained for the four flammability regimes. The minimum value of \( z_c \) obtained for the low flammability, was 0.356 m for an average HRR peak of 100 kW. McGrattan et al. [9] suggested a mesh size in the range of 0.022 - 0.089 m. Based on these results, the mesh size was chosen as the minimum of both criteria (0.02 m) for the different domain regions.

**COMPARISON BETWEEN THE PREDICTED AND MEASURED HRR**

The test of the physic-based model WFDS presented in this study was conducted for the flammability regime with the best reproducibility, which corresponds to the “high and fast flammability”. The LSHR domain, including the extraction hood and the radiant panels, were modelled to fully reproduce the experimental conditions. A preliminary calculation was carried out without the shrub in order to check the modelling of the radiant heat flux emitted by the radiant panels. Predicted and measured radiant heat flux density at a distance of 1 m from the panel were compared and a good agreement was found. Then, the numerical shrub model was configured in front of the radiant panels heated at 520°C. Under these conditions, the simulated amount of energy led to an auto-ignition of the shrub, but it was not enough to sustain the combustion and the spreading within the shrub. Thereby, a numerical piloted ignition, that consist of fuel element particles kept at a temperature of 1000°C, was added. The size of the ignitor was 10×20×20 cm³. It was located in the lower part of the crown like in the experiments. The volume of the ignitor corresponds to the size of the flame observed in the experiment at the time of ignition and the duration was fitted in order to sustain the fire spread (15 s).

Figure 2 displays the predicted and measured HRR over time. The predicted and measured HRR peaks (mean) are in good agreement (230 kW and 228 ± 15 kW, respectively). In addition, the predicted flame duration (56 s) is slightly overestimated compared to the experimental one (44 ± 9 s). It should be noticed that the predicted total combustion duration (flaming and smouldering phases) is shorter than the observed one due to a too fast
extinction of the char after the flameout. Concerning the fuel consumption, 32 % of the fuel was consumed in the simulation. This value is near the experimental one which was 25 ± 6 %. These overall results show the capability of WFDS to reproduce the main measured quantities related to the flammability. However, a plateau in the predicted HRR appeared shortly after the ignition and the extinction occurred too quickly after the flameout. This last phenomenon is probably due to a quicker cooling of the particles with fresh air after the flameout in the simulation compared to the experiments.

Figure 2 : Predicted and measured HRR of the “high and fast flammability” regime over time

CONCLUSION

In this paper the code WFDS was tested for the combustion of a living shrub. Shrubs of rockrose were characterized to obtain the mass proportion and distribution of different classes of particles in order to build a numerical model. Experiments carried out to study the flammability of these shrubs were used as a comparison basis. The numerical test was performed on the flammability that showed the best reproducibility. The mass distribution obtained during the characterization allowed us to develop a numerical shrub of rockrose. Finally, the simulations of the shrub combustion were performed. This study highlighted the capacity of WFDS to predict the peak HRR, flame duration and consumption rate. However, a plateau appeared after the ignition which alters the fire growth. The extinction of the smoldering phase was too fast which could be due to an overestimation of the convective cooling. An investigation on the causes of the plateau through more thorough investigation of the degradation laws (desiccation, pyrolysis and char oxidation) is currently pending.

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