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Numerical prediction of the thermal stress induced by the burning of an ornamental vegetation at WUI

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Abstract

Over the last decades, urban expansion and global warming have increased the occurrence of wildland fires propagating at the vicinity of buildings at WUI. In this scenario, ornamental vegetation is one of the vectors of fire propagation close to habitations, which can significantly increase the risk of damage (Maranghides et al (2009), Maranghides et al (2015), Etlinger et al (2004), Ganteaume et al (2013)). In such context, it is necessary to quantify the thermal stress generated by an ornamental plant over a building to predict the vulnerability of construction materials. To this end, numerical simulation is a good candidate to easily multiply burning cases at field scale and explore the effects. The present study focuses on the predictions of the thermal stress induced by the burning of an ornamental vegetation over targets facing the fire.

The study involves a numerical modelling of the burning of rockrose hedges at field scale using the physics based code WFDS. The solver uses a large eddy simulation approach for fluid dynamics and energy transfer through the fluid phase. The thermal degradation of the solid fuel is modelled (dehydration, pyrolysis, char oxidation) by a three steps mechanism with Arrhenius laws (Mell et al (2009)). The raised vegetation is represented with a Fuel Element approach, which models the solid fuel as a set of static Lagrangian particles of different sizes and distributed within the volume to reproduce the arrangement of the shrub. The ability of WFDS to reproduce the combustion of plants has already been studied at laboratory scales (Mell et al (2009), Perez-Ramirez et al (2017), Morandini et al (2019), Sanchez-Monroy et al (2019), Moinuddin et al (2020)) but investigations at field scale involving raised vegetation are few.

A set of experiments was carried out at field scale. Fire tests consist of the burning of reconstructed rockrose hedges of 6m length, 1m width and two heights (1m and 2m). The geometry mimics the typical shape of ornamental hedges that can be found to separate buildings in south of France. Visible cameras are distributed around the setup to capture the geometry of the flame front. Four couples of heat flux meters are positioned at 3m in front of the centreline and side of the hedge, which represents the theoretical position of the wall of a building according to the current fire safety regulation in France.

Comparison between predictions and experimental data shows good agreement for the local measurement of the heat stress at the location of the targets. Total and radiant heat fluxes fit with experimental data during the fire growth and the fully developed phases, which represent the period where the thermal stress is the highest. Peaks of total and radiant heat flux are the same order value but can be overestimated depending of the location of the sensors due to the wind dynamics that is not fully implementable in WFDS. Results show that the accuracy of the numerical model is satisfying to predict the thermal stress received by targets during the fully developed fire at field scale. It could be used to numerically determine the vulnerability of material buildings in different scenarios.

1. Introduction

The combination of climate change and cities expansion have risen the risk of fire at wildland urban interfaces (WUI) which can lead to house damages and human fatalities. Indeed, one of the identified vectors of fire spreading nearby a dwelling is ornamental vegetation, which can significantly increase the risk of material failure depending of their distance to the walls (Maranghides et al (2009), Maranghides et al (2015), Etlinger et al (2004), Ganteaume et al (2013)). Predicting material thermal stress under wildland fire conditions is a key challenge to help authorities make more efficient fire safety regulations and facilitate the work of firefighters. To achieve this, numerical simulation is a suitable tool that allows to easily multiply fire scenarios at field scale in addition to experiments. While field experiments can be time consuming and expensive, numerical simulations are easier to deploy and lead to a larger number of physical quantities to analyze. However, numerical modeling can involve strong hypothesis compared to actual ambient conditions, especially at field scale since reproducing variable wind conditions is always challenging. Thus, it is required a first step to validate the predictions of the model at field scale by direct comparison with dedicated experiments, which is the topic of the present study. Consequently, this paper is focused on the numerical prediction of the thermal stress induced by the burning of an ornamental vegetation over targets facing the fire and the comparison to experiments. The paper is organized as follow. First, a full description of the experimental scenario at field scale is given. The numerical model employed is then presented, followed by a comparison with the experimental results. Finally, the paper ends with concluding remarks.

2. Experimental setup.

The main goal of this set of experiments is to quantify fire risk incurred by a facade that faces a burning ornamental hedge during summer for two configurations: one that is in accordance with the fire safety regulation in France, and another which is not. The quantification of such risk is directly estimated by measuring the heat flux received at the location of the wall.

Field scale experiments involved a rectangular reconstructed rockrose hedges of 6 m long and 1 m width with 2 different heights (1 m and 2 m) which reproduces the geometry of a common ornamental hedge used to separate buildings in south of France. The hedges were made with steel cages filled with dried rockrose branches rearranged to mimic the natural shape of a shrub. Rockrose (*i.e: Cistus Montpeliensis*) is a common species that can be found in the south of France and which contributes in propagating wildland fires during summer. A $6 \times 2 \times 0.2\ \mathrm{m}^3$ litter made of commercial wooden wool was positioned upstream of the reconstructed hedge to generate a surface spreading fire that ignited the rockrose by direct contact of the flame. The two setups involved 48 kg and 96 kg of vegetation fuel for respectively 1m and 2m height of the hedge, which represents a bulk density of 8 kg/m^3. Rockrose branches were weighted using a weight cell and meticulously introduced into the cage to have the required mass of fuel. Beforehand, rockrose was dried at ambient air to achieve a moisture content on dry basis of 10% in order to consider fuels in extremely dried conditions.

Experiments were carried out during summer under dry atmospheric conditions ($T_{air} = 37.93° \pm 0.37$, $RH_{air} = 16.6\% \pm 1.2$) and low wind conditions ($U_w = 2.29\ m/s \pm 0.17$). Tests were conducted during the same day to avoid variations of weather conditions between 2 consecutive days. Table 1 summarizes the three cases studied. The significant change in wind direction during the tests explain the difference between case n°1 and the others.

Three visible cameras were located around the hedge (2 on the sides, 1 at the back) in order to record the flame geometry. Four couples of radiant and thermal heat fluxes were positioned at 3 m in front of the hedge to assess the heat stress. This distance between the hedge and the heat fluxmeters corresponds to the minimal distance required between an ornamental vegetation and the wall of a building according to the current fire safety regulation in France. The first two couples of fluxmeters were aligned with the hedge centerline at heights of respectively 1 m (R1+T1) and 1.5 m (R3+T3) from the ground. The last two couples were aligned with the side of the hedge at the same z-coordinate i.e. 1 m for (R2+T2) and 1.5 m for (R4+T4). Each couple of fluxmeters was wall-mounted over an $1 \times 0.6 \times 0.05\ \mathrm{m}^3$ insulator plate to protect the wiring and the electronic from the fire. During each experiment, time history of upcoming wind velocity and direction was also recorded using an anemometer placed 15 m upstream from the setup and 2 m height from the ground. The cameras, the fluxmeters and the anemometer were recorded synchronously at 1 Hz using a data logger. Figure 1 presents a photo (a) and a layout (b) of the experiment setup.

Table 1 – Cases setup for the experimental burning of rockrose hedges at field scale

Case n°	**Hedge dimension (m^3)**	**Accordance with Regulation?**	**Wind speed (m/s)**	**Wind direction (°)**	**Relative air humidity (%)**	**Temperature of air (°C)**
1	6 × 1 × 1	Yes	2.34 (±0.73)	-12 (±33)	16.6	37.9
2	6 × 1 × 1	Yes	2.47 (±1.3)	47 (±51)	18.1	37.5
3	6 × 1 × 2	No	2.06 (±0.73)	44 (±43)	15.2	38.4

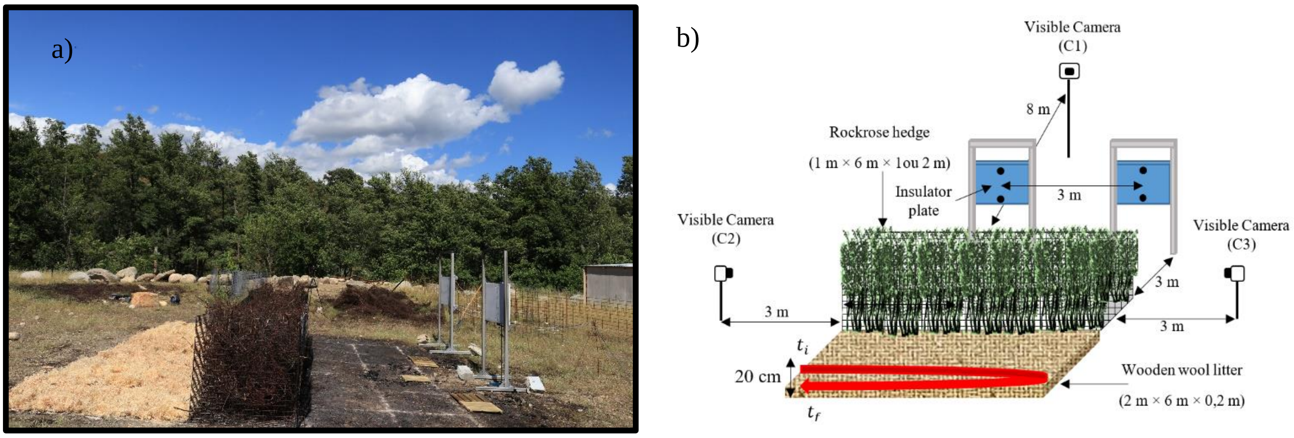

Figure 1 – Experimental setup at field scale: (a) photo of the setup, (b) layout of the setup.

3. Numerical modelling

Wildland-Urban interface Fire Dynamic Simulator (WFDS) is a physics-based CFD solver derived from NIST's code Fire Dynamics Simulator (McGrattan et al (2013a)) that includes the modelling of burning vegetation through a solid fuel approach [2]. Over the last decade, the code was widely use to simulate different types of vegetation fires, ranging from the burning of pine needles at laboratory scale to wildland fires at field scale walls (Mell et al (2009), Perez-Ramirez et al (2017), Morandini et al (2019), Sanchez-Monroy et al (2019), Moinuddin et al (2020)).

WFDS solves a solid-gas phase problem over a numerical domain discretized into a Cartesian grid mesh using the conservation equations of mass, momentum and energy transport. The turbulent gas phase is modelled with a Large-Eddy Simulation (LES) approach and a low-Mach formulation of the Navier-Stokes equations. The solid phase is represented by a "Fuel Element" (FE) approach, which consists in modelling the raised vegetation as static Lagrangian particles of different sizes and properties distributed within a volume that represents the plant. The heat transfer, drag force and thermal degradation for each particle of vegetation are approximated with a one-dimensional approach (thermally thin elements). The degradation of the solid fuel is represented by a three steps mechanism including dehydration, pyrolysis and char oxidation. Each stage is modelled with an Arrhenius law. The combustion of the pyrolysis gas is simplified by a single step combustion equation of a $C_xH_yO_z$ fuel. More details about the solver are in Mell *et al* (2009).

In order to simulate the experiments of the burning hedges, the volume of the numerical domain was set to $50 \times 50 \times 50\ \mathrm{m}^3$ with the hedge positioned at the center. This domain size allows avoiding any interaction between the boundary conditions and the numerical solution close to the hedges. The domain was meshed using two different sizes of hexahedral cells to save computational time. For a zone of $20 \times 20 \times 10\ \mathrm{m}^3$around the hedge, the cell size was $\Delta x = \Delta y = \Delta z = 12.5$ cm which was the best compromise between accuracy and computational cost. In the rest of the numerical domain, the mesh size was $\Delta x = \Delta y = \Delta z = 25$ cm. To reproduce the wind conditions of the experiments, a 1/7th power law profile was used at the inlet for which the averaged wind velocity and direction recorded during the test was considered. At the outlet, an outflow condition was set. On the top and bottom, a free-slip and a wall condition were respectively used. On the sides of the domain, periodic boundary conditions were considered to take into account the wind direction. The rockrose hedge was modeled using a Fuel Element approach and was decomposed into 6 classes of particles: flowers, leaves, twigs of 0-2 mm, 2-4 mm, 4-6 mm and 6-25 mm in diameter. Characteristics and spatial distribution of each particle class were obtained from laboratory measurements. The Arrhenius coefficients associated to the thermal degradation process came from Morandini *et al* (2019). The wooden wool litter was also modeled with a fuel element approach using a three-step thermal degradation model with Arrhenius coefficient taken from Sanchez-Monroy et al (2019). Numerical heat flux sensors (radiant and total) were positioned at the same location as the experimental ones. Figure 2 presents snapshots of the simulations using the rendering of software SmokeView for both cases of hedge height.

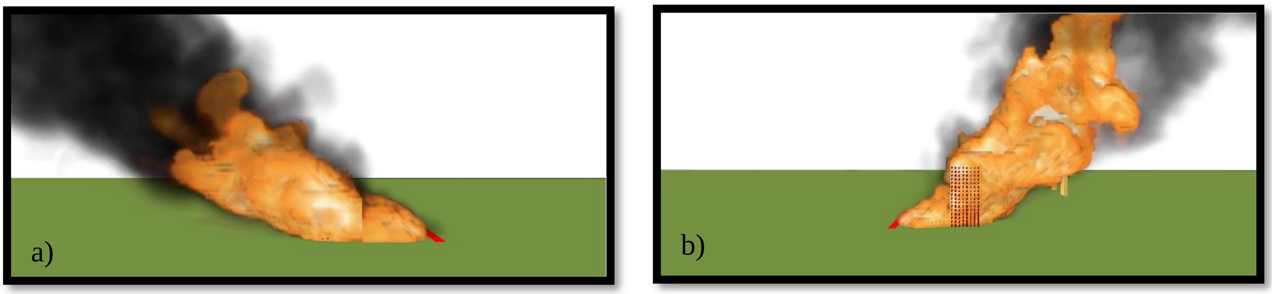

Figure 2 – Snapshots (200 kW/m^3 isosurface) of numerical simulation of burning hedges for two heights: (a) 1m, (b) 2m, rendered in Smokeview

4. Results and discussion

Experimental results show that three combustion stages mainly occur during the burning of the hedge: growth, fully developed fire and extinguishment. The present study focused on the heat fluxes during the developed fire stage. Figure 3 presents an example of the comparison between experiments and simulations for sensors T3 and T4 for case n°1. Red and black dashed lines represent the extinguishment time for the simulations and the experiments respectively. The first observations show that predicted heat fluxes fit better the experiments for the sensors facing the hedge centerline than those located at the side in terms of magnitude and curve shape tendencies.

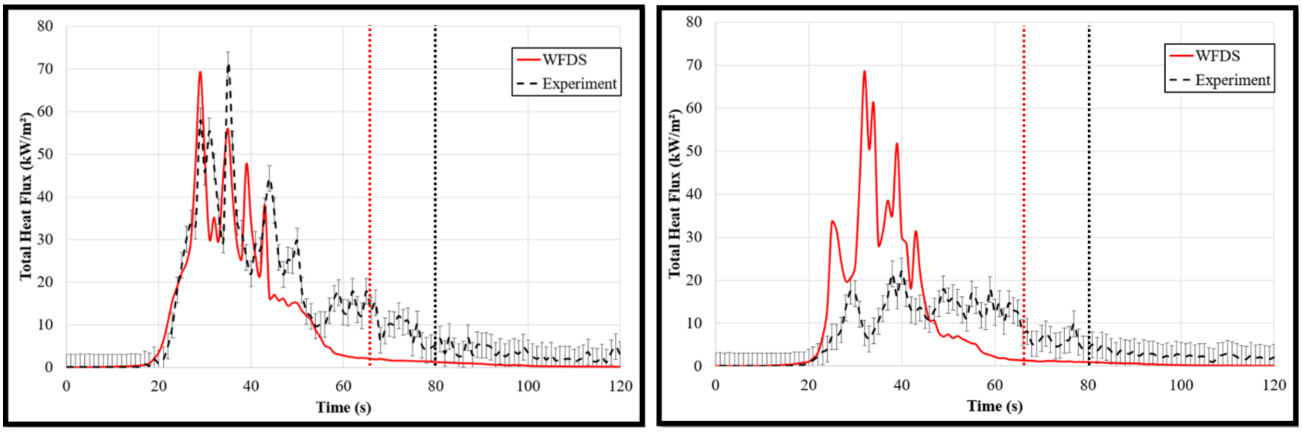

Figure 3 – Comparison between simulation and experiment for the total heat flux line for case n°1: left sensor T3; right sensor T4.

For the sensor T3, the numerical model predicted well the heat flux impinging on the sensor during the first half of the fully developed stage, which shows the highest magnitude of the heat flux. During the second half of the stage, the simulation failed to reproduce the particle collapse observed in the experiments, which deviates the prediction from the measurement. This also causes fire extinguishment occurring 19% to 33% faster in the simulation depending on the case simulated. The edge effects mainly explain the overestimation of the heat flux magnitude received by the numerical sensor at the side. Indeed, experiments have shown that the heat fluxes received by the sensors located at the edge of the hedges are more sensitives to the flame dynamics, and even more when large changes in wind direction occur and lean the flame away from the sensors. The current version of WFDS do not allow reproducing changes in wind speed and direction over time. This leads to a constant orientation of the simulated flames that point toward sensor T2 and T4 during the numerical simulation. The predicted heat fluxes are therefore overestimated the heat fluxes for theses sensors. Overall, comparisons between simulations and experiments are in agreements with observations made by Perez-Ramirez & al (2017) and Meerpeol-Pietri & al (2022) at laboratory scale for pine needles and reconstructed hedges respectively.

Table 2 – Comparison between experimental and numerical exposure times for sensor T3 for each cases at different heat flux threshold.

Heat flux threshold (kW/m^2)	**Exposure time for sensor T3 (s)**								
	Case n°1			**Case n°2**			**Case n°3**		
	Experiment	**WFDS**	**E (%)**	**Experiment**	**WFDS**	**E (%)**	**Experiment**	**WFDS**	**E (%)**
5	62	36	-42	49	37	-24	89	34	-62
8	52	33	-37	39	33	-15	62	31	-50
12	41	30	-27	32	30	-6	51	27	-47
15	33	27	-18	28	28	0	49	26	-47
30	14	11	-21	20	19	5	31	16	-48
35	10	9	-10	18	18	0	26	15	-42
40	7	7	0	14	16	14	20	12	-40
	Average relative difference (%)		-22%	**Average relative difference (%)**		-5%	**Average relative difference (%)**		-48

To evaluate the thermal stress due to the hedge burning, we choose to quantify the exposure times for different heat fluxes thresholds at the sensor location (Meerpoel-Pietri (2021)). Table 2 presents the average predicted and measured exposure time at sensor T3 for each case estimated from the total heat flux curves. According to literature, exposure time measured and predicted are high enough to damage PVC. For instance, for 5 kW/m^2, the loss of mechanical properties for PVC windows or gutters occurs for an exposure time higher than 32 s. This value was exceeded for the experiments and the simulations for all the cases studied.

With regard to the accuracy of the predictions, for all the cases, the accuracy increases when heat flux increases. The hedge collapsing which leads to a longer period of low heat flux measurement during the experiments that cannot be reproduced by WFDS induces this result. In addition, it can be observed that simulation results for case n°3 involving a 2 m high hedge, underestimate the exposure time from 40% to 62% depending on the threshold considered. The hedge collapse observed experimentally and not predicted by the simulation has more impact on the overall hedge combustion for this case. Predictions of the exposure time for cases n°1 and 2 show good agreement. While average relative difference is around 5% for case n°2, case n°1 underestimates the exposure time by 22% in average and up to 42% for the lower heat flux because of changes in wind dynamics as explained previously. According to these results, this study validates the capability of WFDS to be used for the prediction of material failure at field scale for cases that includes vegetation up to 1 m height.

5. Conclusion

Comparison between dedicated experiments and numerical simulations were carried out to demonstrate the capability of WFDS to predict thermal stress induced by the burning of reconstructed hedges at field scale. Three sets of experiments involving 2 sizes of hedges were carried out in summer to reproduce two configurations: the first one that corresponds to the current fire safety regulations in France and the second one that does not agree. Results are in accordance with literature and show that WFDS gives good predictions of the total heat flux received and the exposure time at the hedge centerline during the period where the fire is the most intense. However, predictions deviate from the experimental data when changes in wind direction occur during the experiment and for the 2 m high hedge which strongly collapsed during the burning phase.

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