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Physics-based modelling of junction fires: Sensitivity and Validation studies

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Abstract

The process of modelling and replicating extreme fire behaviour like junction fire, which is the intersection occurred between two contiguous fire lines, is essential for understanding the phenomena associated with extreme fires. Numerical simulations of junction fires, replicating laboratory-scale experiments, with no imposed wind, were performed for a shrub fuel bed with slopes ranging from 0° to 30°. The simulations of junction fires were conducted for two junction angles 30° and 45°. For each scenario, the sensitivity to a range of numerical parameters was investigated.

The rate of spread (ROS) is a key parameter for assessing risks from vegetation fires. Experimental spreading junction fires, conducted at laboratory scale at Coimbra University (Portugal), were simulated using FIRESTAR3D −a three-dimensional physics-based fire model. To ensure the robustness of simulations, sensitivity analyses were carried out by varying the grid resolution, domain size and fuel characteristics −using two descriptions levels of the shrub: the vegetation was represented using only one cylindrical-shaped solid-fuel type (excelsior fuel using the characteristic parameters for Erica shrub), or two fuel by adding the contribution of twigs of various diameters up to 6 mm while keeping the same packing ratio. Finally, the validation of FIRESTAR3D simulations was achieved through the comparison of predicted and experimentaly-measured ROSs.

The experimental trends of the compared quantities were well reproduced by the simulations. Accelerating and decelerating propagation phases were observed in all simulations, with a dependence on the slope angle, while the maximum ROS depends critically on the junction angle. As it was the case of other wildfires simulated by FIRESTAR3D, it was found that this physics-based model is capable of simulating junction fire propagation.

There are several processes associated with the development of a junction fire behaviour, in which dramatic changes in fire behaviour can occur with little change in various fuel, weather and topographical parameters. In a subsequent study, we aim to develop an understanding of junction fire behaviour taking into account essential parameters that affect the behaviour, namely: slope, junction angle, and driving wind velocity.

1. Introduction

Fire behaviour in extreme form is one of the major natural disasters in many parts of the world given their devastating effects. The intersection of multiple fire lines is among the strongest form of extreme fire behaviour. A junction fire, also called jump fire or eruptive fire, is the case of merging of two fire fronts, enhancing their propagation speed through strong interaction that occurs between the two fire lines. A particularly serious example took place during the 2003 Canberra (Australia) fire, where fire merging led to a devastating intense fire which spawned the first known pyrogenic tornado (McRae, et al., 2013). To mitigate the impact of this natural hazard, there is a need to better understand the wildfire behaviour. Simulation tools are designed to forecast fire behaviour and the course of a fire front over landscapes on a broad scale, while describing the intricacies of the interaction between flames and possible targets on a smaller scale (houses, vegetation, etc.).

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The present study is focused on the specific eruptive fire mechanism of the merging of contiguous fire fronts, called junction fires. The analysis and the estimation of the evolution of the junction fire fronts were conducted using a physics-based model FIRSTAR3D (Morvan, et al., 2018). This three-dimensional model, developed in close collaboration between Aix-Marseille University, the Lebanese University, and Toulon University, is based on a multi-phase formulation and solves the conservation equations of the coupled system formed by the vegetation and the surrounding gaseous medium. The model takes into account the vegetation degradation processes (drying, pyrolysis, and combustion), the interaction between the atmospheric boundary layer and vegetation (aerodynamic drag, heat transfer by convection and radiation, and mass transfer), and the transport in the gaseous phase (convection, turbulence, and combustion).

There has been limited research into the interactions of junction fires especially using a physics-based model, and it is desirable to count this study as an endeavour to replicate the behaviour and examine the influence of the critical parameters: slope and junction angle.

Physics-based modelling is a very complex approach and the complexity comes also from the numerous thermo-physical and numerical parameters used in the simulations. The sensitivity of the simulations to the grid resolution, domain size and fuel description level were investigated in this study. Sensitivity analysis to numerical parameters has been carried out with a twofold objectives: to assess the suitability of the numerical implementation of the junction fire configuration and show the advantage of considering several fuel types to represent the vegetation, and to determine the most appropriate grid resolution to be used within the vegetation, as well as the acceptable size of the computation domain.

2. Methodology and Numerical modelling

Raposo, et al. (2018) conducted a large series of experimental junction fire tests at laboratory and field scales. The laboratory experiments were carried out at the Forest Fire Research Laboratory (LEIF) of the University of Coimbra, Portugal. The experiments reported in Raposo, et al. (2018) provide many experimental measurements that could be used to validate the present simulation results. The rate of spread (ROS) is the quintessential parameter to quantify the dynamic behaviour, although other simulation outputs such as fire intensity, dominant heat transfer quantities, and flame geometry are also important.We examined the capability of FIRESTAR3D to reproduce the results of such experiments for slope angles ranging from 0 to 30°, and for two values of the junction angle (30° and 45°), and for multiple values of fuel moisture content (see Table 1). Additional simulations were carried out (simulation 6 in Table 1) as a part of the parametric study. Simulations of this kind, are computationally expensive due to the high spatial resolution (grid size of 5 cm in the propagation direction) and temporal resolution (10^{-3} to 10^{-2} s) required to accurately solve the governing equations of the problem.

Table 1- Physical parameters of the junction fires cases considered in the validation study.

Simulation Number	ID in (Raposo, et al., 2018)	Fuel moisture content, m_f (%)	Junction angle, Θ (º)	Slope angle, α (º)
1	10-L48	23.91	45	30
2	11-L49	23.91	30	0
3	12-L50	21.65	30	30
4	13-L51	18.76	30	20
5	17-L56	13.63	30	30
6	-	20	60	30

Numerical simulations were conducted using a V-shaped vegetation region immersed inside a larger computational domain (29 m long, 29 m wide, and 12 m high) as shown in Figure 1. The homogeneous fuel bed, of height 0.15 m, is 5 m long and is located 12 m away from the inlet boundary and at least 12 m (depending on the junction angle) away from the lateral boundaries. Solid-fuel particles are assumed to have a cylindrical shape and to behave as a black body. Both the solid-phase and the fluid-phase grids are characterised by cells sizes below the extinction length scale (0.073 m) within the vegetation, given by $\frac{4}{\alpha\sigma}$, where α is the packing ratio and σ is the surface-to-volume ratio (see Table 2).

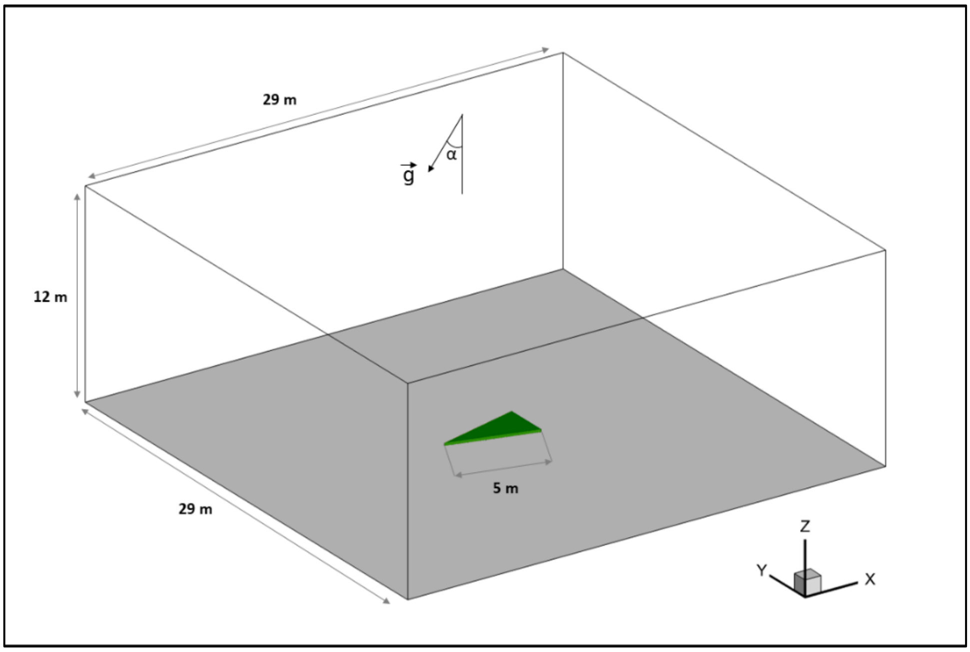

Figure 1 - Perspective view of the computational domain and the vegetation cover used to simulate the junction fire.

The fire lines are ignited in the model by activating a burner. A 10-cm wide burner is activated instantaneously along the entire ignition lines by injecting CO gas at 1600 K from the bottom of the computational domain for the duration of 5 s. Open boundaries are applied on the computational domain sides (except the bottom one), which allows the fire to create its own induced air flow. The main physical parameters that were used in all the configurations are tabulated in Table 2.

Table 2- Geometric and physical properties of the shrubland vegetation (Raposo, et al., 2018; Gilliers, et al., 2002).

Vegetation height δ	Solid-fuel volume fraction, α	Surface/Volume ratio, σ	Dry material density, ρ	Drag Coefficient, C_D	Thermal emissivity	Vegetation particles shape
(m)		(m^{-1})	($Kg.m^{-3}$)			
0.15	0.00784	6900	500	0.42	1	Cylindrical

The fuels used in this study were shrubs composed of a mixture of genus Erica, often called Heather, the fuel load was kept constant at the value of 0.6 $kg.m^{-2}$, used experimentally.

The physical properties of the shrub mentioned in Table 2 are characteristic properties (Pereira, et al., 1995). Realistic simulations should take into account the heterogeneity of fuel in terms of distribution of twigs and leaves, their percentages, as well as their specific surface-to-volume ratio. Most of the physical properties of shrubs used by (Raposo, et al., 2018) can be found in the literature (Fernandes, 1997) and a complex method of describing shurb (combination of leaves and twigs) is presented as Table 3. A simulation was carried out using this fuel description to observe any difference of fire behaviour compared to fuel of Table 2. For both descriptions, the same fuel moisture content was considered (same to experimental value).

Table 3- Geometric and physical properties of leaves and twigs of shrub vegetation (Fernandes, 1997).

	Surface/Volume ratio, σ (m^{-1})	Dry material density, ρ ($Kg.m^{-3}$)	Solid-fuel volume fraction, α
Leaves (d < 2.5mm)	7200	253	0.0108 (70%)
Twigs (2.5 < d < 6 mm)	920	970	0.001212 (30%)

Although the grid resolution is chosen below the extinction length, (Perez-Ramirez, et al., 2017) recommended to use a grid cell size three times less than the extinction length. Mesh and domain size sensitivity tests have been carried out by increasing and decreasing of the cell size by 30%. To that end, several simulations were carried out using cells of different sizes: 3.5, 5 and 6.5 cm. Moreover, three sizes of the computational domain with a distance from the vegetation region to the open boundaries of 10, 12 and 15 m have been considered, as detailed in Tables 4 and 5.

Table 4- Mesh parameters (for a computational domain size of 29×29×12 m^3).

Minimum cells size in the xy plane	3.5 cm	5 cm	6.5 cm
Mesh size of the solid phase	284×284×18	200×200×12	152×152×8
Mesh size of the fluid phase	202×202×163	160×160×160	136×136×158

Table 5- Domain size (with a cell size of 5 cm).

Size	***1***	***2***	***3***
Domain size	25×25×10 m^3	29×29×12 m^3	35×35×15 m^3
Mesh size of the fluid phase	150×150×134	160×160×160	176×176×199

3. Results and Discussion

In order to capture the effects of parameters and to consistently compare flame properties, quasi-steady regions of acceleration and deceleration were identified. These regions were duly identified for all selected simulations, similarly to the experimental work that proves a pattern of behaviour directly related to the selected parameters.

Six duly-chosen configurations (see Table 1 for details) were simulated using FIRESTAR3D. the comparison between the simulations and the experiments is based on the measurement of the ROS of the junction point assumed to lie in the mid plane of the computational domain.

3D views of the fire flame obtained for a simulation 5 is represented in Figure 2. These results show clearly the potential of FireStar3D in reproducing numerically the junction fire in shrubland.

Assuming a symmetrical propagation, we computed the ROS by tracking the local consumption of dry material in the central vertical plane along the streamwise direction inside the vegetation (at 5cm from the bottom). The ROS estimation was obtained from the time derivative of the position of the junction point.

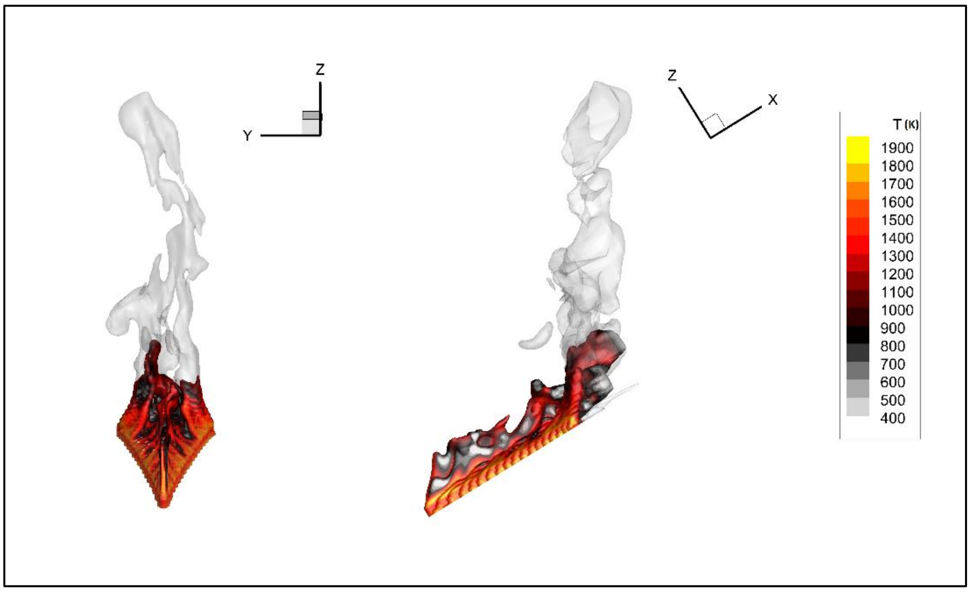

Figure 2- 3D front (left) and side (right) views of an isovalue surface of the soot volume fraction (1.6×10^{-7}) coloured by the gas temperature and an isovalue surface of the water mass fraction (9×10^{-3}) (in grey with 50% of transparency) obtained in the case of simulation 5, 10s after ignition.

3.1. Sensitivity analysis results

Figure 3 shows simulation results of junction point position as function of time from the cases listed in Tables 4-5. Minimal effects of the grid resolution and the domain size on the junction point propagation are observed. Consequently, the considered domain size and mesh (Size 2 – Mesh 5 cm) allow to obtain a solution that is quasi-independent of these parameters as far as global fire behaviour is concerned (ROS, fire intensity, etc).

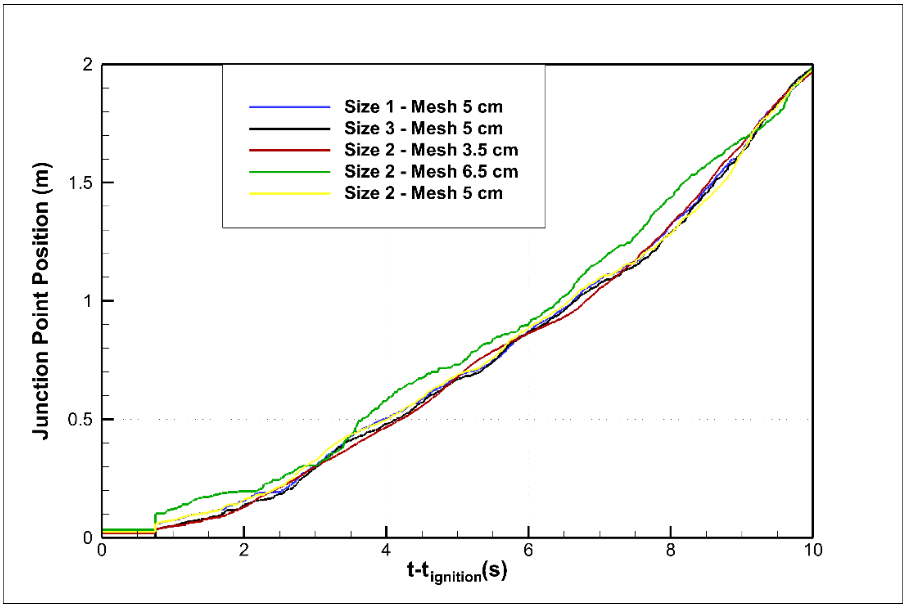

Figure 3- Junction point position for simulation 2 in five sensitivity tests.

Regarding fuel description level, the shrub was described using two methods. In both cases the total initial volume fraction and mass were kept the same (see Table 3) and they are identical to those reported in (Raposo, et al., 2018). A more realistic description of the vegetation (by accounting for different sizes of solid fuel particles) better reproduced the fire dynamics, especially the mass loss process.

Regarding the ROS, a good similarity of the junction point propagation for single and two types of fuel is observed (see Figure 4). The propagation is slightly quicker in the two-fuel case and we attributed that to the low percentage of large diameter particles and very small surface to volume ratio (diameter) of small particles comparing it to the characteristic value adopted first (6900 m^{-1}). Besides that, the limited information about moisture content of leaves and twigs, accounts for the slight overestimation. Overall, the use of multiple description level manages to estimate the ROS in a similar order of magnitude.

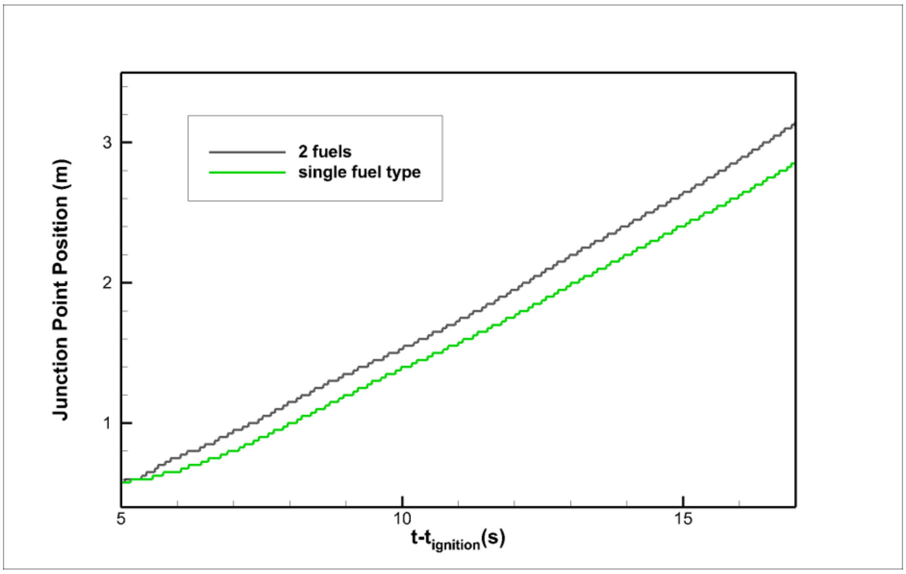

Figure 4- Junction point position for the different fuel combinations

3.2. Validation results

Figure 5 shows the evolution of fire perimeters. It can be observed that the junction fire angle is not fixed during the propagation, instead, it (on average) increases continuously.

The process of merging of these fires is not the closure of the space between the fire lines by a reduction of their respective angle, similar to the closure of scissors. On the contrary, it is the junction point that advances, tending to form a single straight fire line resulting from the two original fire fronts.

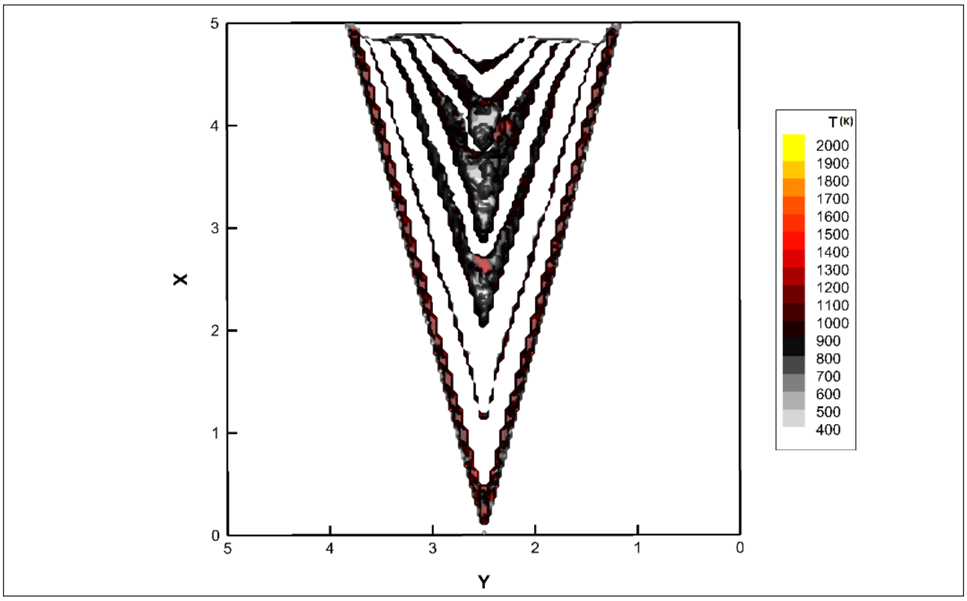

Figure 5- Evolution of fire perimeter according to pyrolysis edge (dry material 0.001 kg.m^{-3}) for simulation 2. The first perimeter is at t – t$_{ignition}$ = 5s and the time difference between each perimeter is 5s.

Simulations 2, 3 and 4 have the same junction angle (30°) and close fuel moisture content values (21.35±2.55%), whilst the slope angle varies (0°, 20° and 30°). Figure 6 shows the simulation and experimental results of ROS for these three simulations.

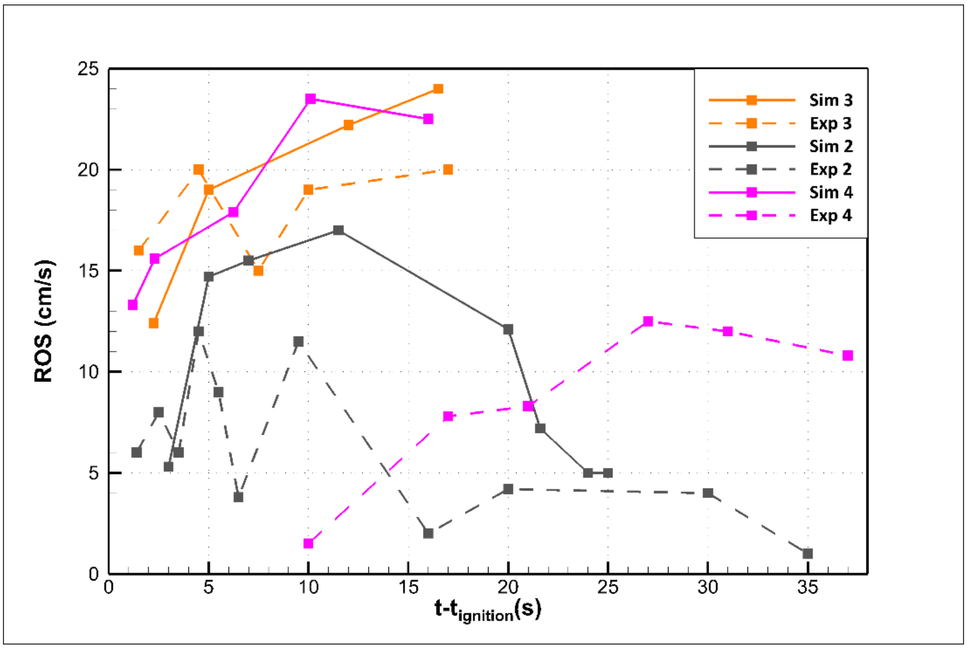

Figure 6- Evolution of the value of ROS for three different slope values (α) as a function of time.

First and foremost, the behaviour under the change of slope angle is prominent in the simulated ROS' results. Taking the maximum ROS into consideration, the value increases with the increase of slope angle (cm.s^{-1} for slope 0°, 23.5 cm.s^{-1} for slope 20° and 25 cm.s^{-1} for slope 30°). Experimentally, case number 4 seems to be not reflecting this effect as the maximum value (12.5 cm.s^{-1}) is close to the maximum value for experiment 2 (12 cm.s^{-1}) and way far from 20 cm.s^{-1}, maximum value for case 3. This could be attributed to fluctuations that occurred in experiments or ROS measurement error.

The existence of acceleration and deceleration propagation phases has been observed in simulations as observed in experiments. The deceleration phase was significant in simulation 2 (α=0°), slight in simulation 4 (α=20°) and absent in simulation 3 (α=30°).

Experiments 3 and 5 were conducted with the same angles but the fuel in experiment 5 was drier (8% fuel moisture content difference). The simulations capture this difference only by a slight increase in the maximum ROS, however, the accelerative behaviour did not change.

3.3. Parametric study

In Simulations 1, 3 and 6, the slope is 30° and the junction angles are 45°,30° and 60°, respectively. The fuel moisture content values are close; therefore, the effect of junction angle could be deduced. The results are depicted in Figure 7.

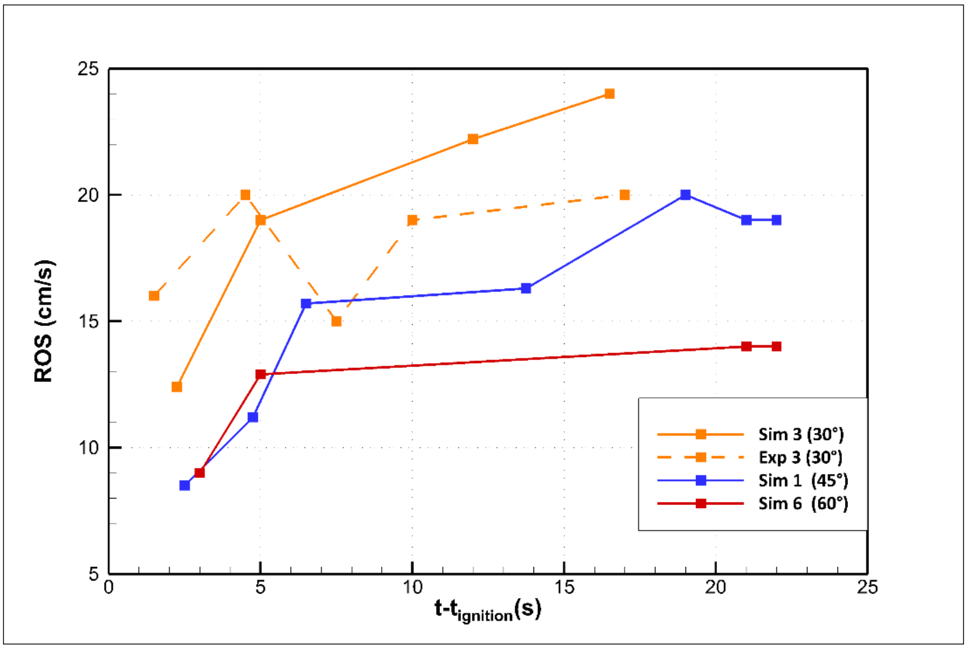

Figure 7- Evolution of the value of ROS for three different junction angles (θ) as a function of time.

Comparing Figures 6 and 7, it appears that the junction angle is more important parameter on the fire spread, consistent with the findings of (Viegas, et al., 2012) for non-slope conditions. A thorough investigation for the influence of critical parameters for a wider range were done in a full parametric study published in a forthcoming paper (Hassan, et al., 2022). Considering simulation 3 and 1, an increase of 15° of junction angle decreased the maximum ROS by 5 cm.s^{-1}, which correctly reflected the experimental results.

4. Conclusion

A set of junction fire simulations was conducted numerically using a physics-based model. The use of physics-based models to simulate extreme fires offers the possibility to study, in detail and at a low cost, the burning of vegetation according to a wide set of parameters that are difficult to control experimentally. FIRESTAR3D has been validated for junction fire simulations by comparison ROS estimation to an experimental data set, proving an excellent quantitative and qualitative accordance. The ultimate objective of the study is to investigate the effects of the slope, the junction angle and the wind speed on fire behaviour during the different propagation phases and on the ROS, endeavouring to build a better understanding of the junction fire phenomenon and its underlying physics.

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