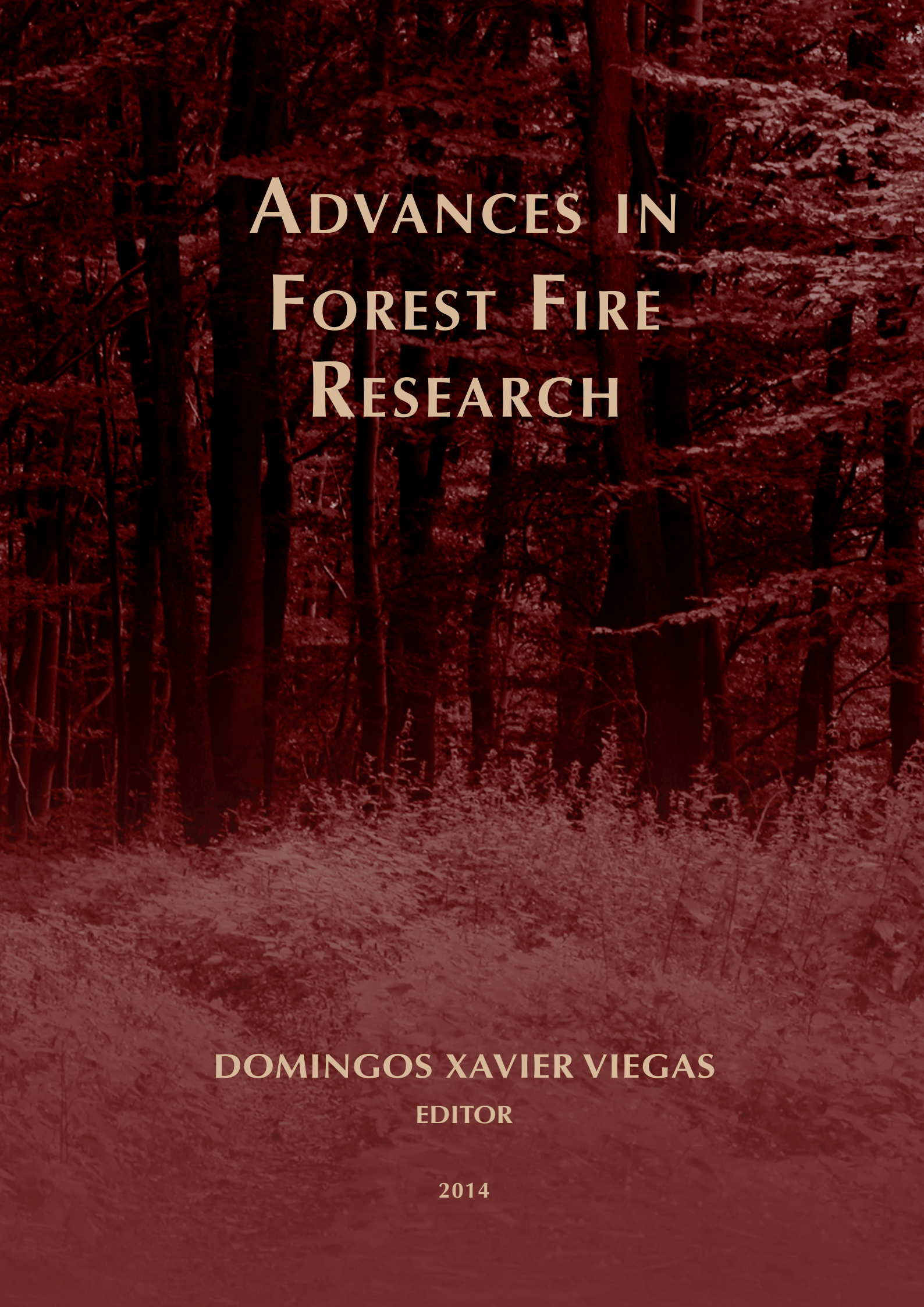

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FireStar3D: 3D finite volume model for the prediction of wildfires behaviour

G. Accary [a], S. Meradji[b], D. Morvan[c,d], O. Bessonov[d], D. Fougère[e]

[a] *Beirut Arab University, Tripoli, Lebanon, g.accary@bau.edu.lb*
[b] *IMATH, EA 2134, Université de Toulon, Toulon, France, meradji@univ-tln.fr*
[c] *UNIMECA, Aix-Marseille Université, Marseille, France, dominique.morvan@univ-amu.fr*
[d] *M2P2, UMR 7340 CNRS - Aix-Marseille Université, Marseille, France, dominique.fougere@univ-amu.fr*
[e] *Institute for Problems in Mechanics RAS, Moscow, Russia, bess@ipmnet.ru*

Abstract
Most of the operational tools of fire propagation in natural environment are based on statistical or semi-empirical approaches. However, under conditions that deviate from the database used to construct these models, extrapolation may be completely random and, therefore, not very reliable. Subsequently, other models have been developed, taking into account the various interactions occurring between the vegetation and the surrounding fluid medium. This approach is based on a very detailed modeling of the physicochemical phenomena involved in a fire that are quite complex (turbulence, combustion, radiation, interaction between the fluid and vegetation ...). The 3D model developed in this work (referred to as "FireStar3D") is part of the latter class of models, and consists in solving the conservation equations of the coupled system consisting of the vegetation and the surrounding gaseous medium. The model takes into account the phenomena of vegetation degradation (drying, pyrolysis, combustion), the interaction between an atmospheric boundary layer and a canopy (aerodynamic drag, heat transfer by convection and radiation, and mass transfer), and the transport within the fluid phase (convection, turbulence, gas-phase combustion). This paper presents the validation of this 3D model that was conducted for a fire in confined environment, by reproducing experiments of fuelbed fire in a wind tunnel carried out by Catchpole *et al*. in 1998. The comparison between the simulations and the experimental data is mainly based on the rate of spread of fire or ROS (velocity of the fire front). A good agreement is obtained for most of the simulations that were conducted, and a study of the dependence of the rate of spread on the wind speed and on the fuel bed characteristics, particularly the fuel moisture content, is carried out.

Keywords*: Forest fires, turbulent reactive flows, modelling and numerical simulation, high performance computing.*

1. Introduction

As evidenced by the literature, most of the operational tools of fire propagation in natural environment are based on statistical or semi-empirical approaches [1]. However, under conditions that deviate from the database used to construct these models, extrapolation may be completely random and, therefore, not very reliable. Subsequently, other models have been developed; in these models, the study of the spread of a fire and its behavior are addressed through its physicochemical aspects, taking into account the various interactions occurring between the vegetation and the surrounding fluid medium [2]. This multiphase approach is indeed based on a very detailed modeling of the physicochemical phenomena involved in a fire that are quite complex (turbulence, combustion, radiation, interaction between the fluid and vegetation, ...). To better understand the phenomenon of the spread of fire in natural environment, the model developed in this work is part of the latter class of models, and consists in solving the conservation equations of the coupled system consisting of the vegetation and the surrounding gaseous medium [3]. This model is already operational in a 2D approximation [4] and

consists in solving the multi-physical model in a vertical plane defined by the direction of fire propagation. The 3D extension of the existing model enables to render the 3D effects observed in real fires and to represent the real heterogeneous structure of the vegetation. The objective of this paper is to evaluate the potential of this 3D model (referred to as "FireStar3D") that has been mainly developed within the context of the European integrated project "FireParadox". This leading evaluation was conducted for a fire in confined environment by reproducing experiments of fuelbed fire in a wind tunnel (the so-called Rothermel configuration), carried out by Catchpole *et al*. in 1998 [5].

2. Modelling and Numerical Method

The present multiphase formulation, detailed in [3, 4, 6, 7], is based on the description of the behaviour of the coupled system formed by the vegetation and the surrounding atmosphere. The model consists of two parts: one part devoted to the calculation of the turbulent-reactive fluid flow resulting from the mixture of the pyrolysis and combustion products and the ambient air, and a second part devoted to the evolution of the state of the solid vegetation subjected to the intense heat flux coming from the flaming zone. Each solid fuel particle is assimilated as a mixture of water, dry foliage (or dry wood), char, and residual ashes. During fire propagation, the degradation of the vegetation is represented using a three steps temperature-dependent mechanism (drying, pyrolysis, and char oxidation), where the constants (activation energy and pre-exponential factor) are evaluated empirically from thermo-gravimetry Analysis (TGA), performed for solid fuel samples [6]. It is assumed that the pyrolysis process can be activated only if the dehydration was completed, and that the surface oxidation can begin only if the pyrolysis was completed. The gas flow around the fire is considered to be fully unsteady and turbulent. To extract a coherent behaviour, the balance equations (mass, momentum, energy, and chemical species) governing the time evolution of the fluid phase are filtered using a weighted average RANS (Favre) formulation [8]. The interaction between the ambient atmosphere and the vegetation is taken into account through additional terms in the equations (gas production due to pyrolysis reaction, drag force, heat transfer by convection and radiation exchange with solid phase, …). The closure of these equations is done using an eddy viscosity concept [9], evaluated from the turbulent kinetic energy and its dissipation rate. An adapted statistical two-equations (k-Epsilon)-RNG version turbulence model in a high Reynolds number formulation is employed [10,11]. The Eddy Dissipation Concept (EDC) combustion model [9,12] is used to evaluate the combustion rate in the gaseous phase, where it is assumed that the reaction is mainly limited by the mixing rate between the pyrolysis and the oxygen of the ambient air. Convection and radiation heat transfers between the hot gazes, the flame, and the unburned solid fuel are taken into account as follows: the convection heat transfer coefficient is modelled using empirical correlations [13] and the radiation heat transfer is obtained by solving the radiation transfer equation (RTE) [14] in which the contribution of the flames (soot particles) and the embers is included [3]. The fluid enthalpy-temperature dependence is treated using the CHEMKIN thermodynamic database [15]. Finally, the soot volume fraction field is obtained by solving a transport equation [16,17] including a thermo-phoretic convective contribution [3] and a soot oxidation term [18].

The fluid flow conservation and transport equations are solved numerically by a fully implicit finite volume method in a segregated formulation [19]. "FireStar3D" predicts turbulent reacting flows in rectangular domains on a structured but non-uniform staggered mesh. The time discretization relies on a third order Euler scheme with variable time step. To ensure the numerical stability, the space discretization is based on second order schemes with flux limiters (Quadratic Upstream Interpolation scheme [20] and ULTRA-SHARP [21]) for convection terms while diffusion terms are approached by central difference approximation with deferred corrections [22] to maintain accuracy. The Radiative Transport Equation (RTE) is solved using a Discrete Ordinate Method (DOM), consisting in the decomposition of the radiation intensity in a finite number of directions. This set of discrete contributions is integrated using a numerical Gaussian quadrature rule (a S8 method is used) for the

calculation of the total irradiance [23]. The set of ordinary differential equations describing the evolution of solid fuel are solved separately using a fourth order Runge-Kutta method. From implementation point of view, the code is parallelized [24] and optimized [25] using the APIs OpenMP and HMPP directives (suitable for shared memory platforms and accelerators) and is operational on a high-performance computing machines consisting of a SMP node using modern processors with INTEL Xeon Phi co-processors and NVIDIA graphic cards. Finally, the hydrodynamic module of the code has been extensively validated on several benchmarks of laminar and turbulent natural convection, forced convection and neutrally stratified flow within and above a sparse forest canopy [26-31].

3. Rothermel configuration

As mentioned in introduction, in the framework of validating "FireStar3D", several experiments of fuelbed fire carried out by Catchpole *et al*. in a wind tunnel are reproduced numerically. Figure 1 shows a perspective view of the flow computation domain; all the simulations were carried out using the same geometric parameters and the depth of the fuel bed δ was fixed at 20.3 cm. The fuel bed is divided into two zones that have the same characteristics, however only zone (2) is thermally degradable. Zone (1) was added to account for the wire mesh spoiler used in the experiment that was placed on the floor of the wind tunnel from wall to wall, 2 m upwind the fuel trail, and was adjusted to have the same height as the fuel depth; as mentioned by Catchpole *et al*., this wire mesh was placed in order to simulate a longer reach of the fuel and its resulting turbulent boundary layer. Also, vertical strips of metal sheeting (25 cm high) were placed in the experiments along each side of the tray to mimic a wider fire front by preventing indrafts into the combustion zone. These strips were accounted for numerically by placing vertical baffles along each side of the fuelbed (see Figure 1); the velocity component normal to the baffles (y component) is set to zero, while a drag coefficient $C_D = 1.0$ (based on the baffles exposed surface) was introduced in the momentum equations of the velocity components tangential to the baffles (x and z components). The value of the drag coefficient $C_D = 1.0$ resulted in a quasi-uniform fire-front, as observed experimentally.

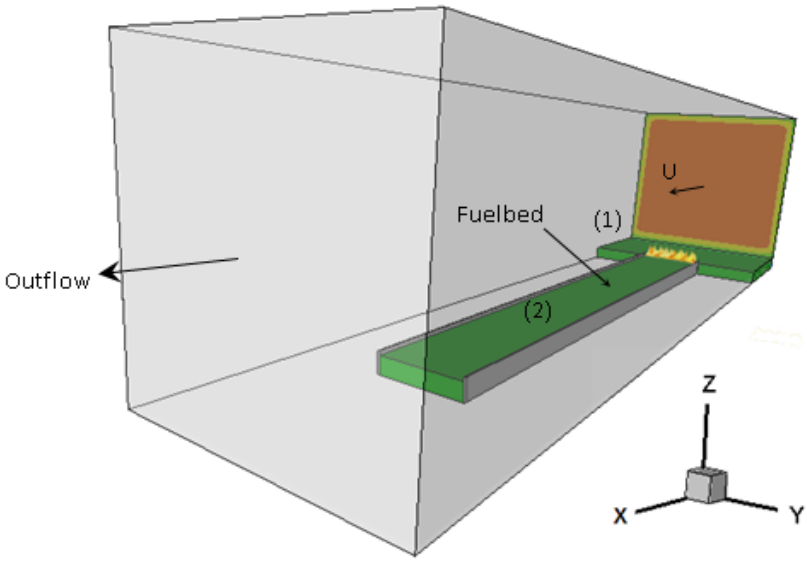

Figure 1. Perspective view of the computation domain corresponding to Catchpole et al. experiment. The flow domain dimensions are 12×3×3 m3 and those of the fuel bed are 10×1×δm3 (δ = 20.3 cm). The fuel bed is divided into two zones, only zone (2) (2m < x < 10m) is thermally degradable, vertical baffles (25 cm high) are placed along both sides of zone (2) and fire is set at its entrance.

Before ignition, simulations were run long enough using Neumann conditions at the open boundaries while maintaining a negative pressure gradient in the x-direction that was adjusted in order to reach a turbulent steady state with the desired mean wind speed that was imposed in the experiment; 5 seconds were sufficient for this phase. Then, the turbulent velocity profile, obtained at channel inlet at the end of this phase, is applied (as a Dirichlet condition) at the inlet of the domain during the remaining time

of simulations. At t = 5 s, fire is set at the entrance of zone (2) by injecting carbon dioxide at 1600 K from the bottom of the computation domain for another 5 s. The injection surface lies between x = 2 m and x = 2.16 m, and along the entire width of zone (2). At t = 5 s, the average injection velocity is at its maximum (V_j = 10 cm/s), then it decreases linearly with the burned mass of dry material (m_b) according to the equation (1) in order to avoid destabilizing the fire-front by suddenly ceasing the injection.

$$V_j(cm/s) = 10 \times \left(1 - \frac{m_b}{m_{b0}}\right) \quad (1)$$

where m_{b0} is the initial mass of dry material located above the burner (i.e. the mass of dry material inside the volume $V_{b0} = 0.16 \times 1 \times \delta$ m^3). Eq. (1) is used between t = 5 s and t = 10 s as long as V_j remains positive, injection of carbon dioxide is ceased if V_j reaches zero during this time interval.
Several simulations were conducted for different wind speeds and for different moister contents of the fuelbed. The simulations correspond to experiments EXMC 23, 24, 28, 36, 48, and 69 carried out by Catchpole *et al*., in which regular excelsior is considered; the main physical data of the simulations are shown in Tab. 1. A wall-refined mesh of 300×80×62 grid points was used for the fluid domain, while a uniform mesh was used for the solid domain with a grid size (Δx, Δy, Δz) = (2 cm, 1.25 cm, 1.69 cm). Since a high-Reynolds turbulence model is used in the simulations, the fluid domain mesh was carefully chosen to be fine enough for an accurate description of the solution, while respecting the condition $11.5 < y^+ < 500$ during the entire simulations time. The results were obtained using an adaptive time-step strategy based on a local truncation error approach, with time steps in the range of 0.001 to 0.01 seconds. At each time step, the conservation and transport equations were solved with an accuracy of 10^{-4} in normalized form.

Table 1. Rothermel configuration experiments chosen to show the effect of wind speed and moister content on fire spread dynamics. δ - fuelbed depth, U - wind speed, α - packing ratio, σ - surface area to volume ratio, M - moister content. Regular excelsior (particles density ρ_P = 398 Kg/m^3) is considered in all experiments.

	σ (m^{-1})	α	δ (cm)	U (m/s)	M (%)
EXMC23	7596	0.005	20.3	2.68	5.5
EXMC24	7596	0.005	20.3	0.89	5.2
EXMC28	7596	0.005	20.3	1.79	5.4
EXMC36	7596	0.005	20.3	2.68	10.1
EXMC48	7596	0.005	20.3	2.68	18.0
EXMC69	7596	0.005	20.3	2.68	3.0

4. Results

Figure 2 shows the temperature field obtained at t = 15 s (i.e. after 10 s of burning) in the simulation corresponding to experiment EXMC23 in Tab. 1 (U = 2.68 m/s and M = 5.5%); figure 2 shows the development of the flame and the expected propagation of fire. Figure 3 shows the corresponding distributions of temperature and dry material fraction at fuelbed-surface; figure 3 shows clearly the quasi-uniform fire-front obtained experimentally as mentioned in the previous section, and we notice also that the fuelbed upstream the ignition line (at x = 2 m) remains intact during the entire simulation time.

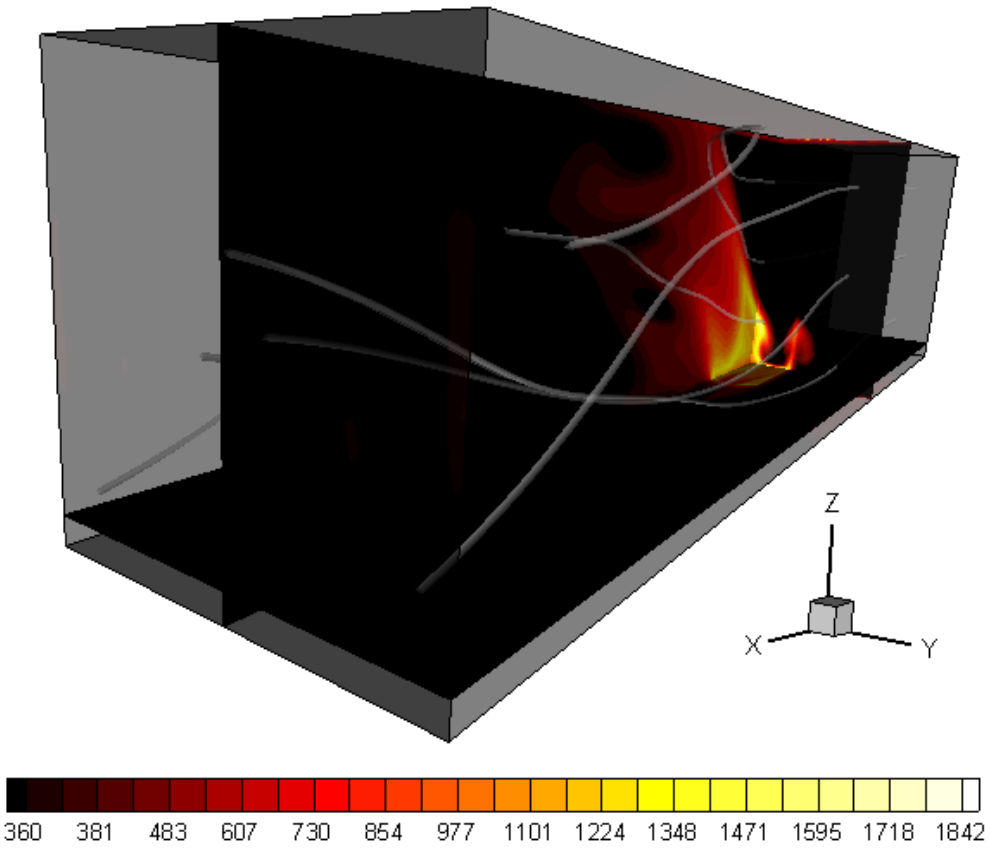

Figure 2. Temperature field and some streamlines obtained at t = 15 s, corresponding to experiment EXMC23 of Catchpole et al. (regular excelsior, wind speed of U = 2.68 m/s, moister content 5.5%, see Tab. 1 for more details).

The comparison between the simulations and the experimental data is based on the rate of spread of fire or ROS (i.e. the average velocity of the fire front). For this purpose, fuelbed characteristics were monitored at several positions along the line (y = 1.5 m, z = 0.203 m) as shown in Figure 4, by analogy to the photocell tubes positioned at 0.5 m intervals in Catchpole *et al*. experiments. Figure 5 shows the time evolution of the fuelbed temperature at duly chosen points of Figure 4; we clearly notice the phases of pyrolysis and char combustion. Indeed, according to the solid-fuel combustion model implemented in "FireStar3D", pyrolysis of dry material takes place between 400 K and 500 K, while char combustion starts once all dry material at a given location has been consumed. The ROS could be easily estimated from Figure 5 by measuring the average time required for the pyrolysis front (isotherm 500 K) to move from a monitoring point to another (covering each time the distance of 0.5 m). However, a simpler and more accurate method for estimating the rate of fire spread consisted in finding at each time step of simulation the average position of the pyrolysis front at the fuelbed surface. This was done by determining the average positions of the furthest points downstream the ignition line where the dry material fraction is equal to zero. In Figure 3(a), we clearly distinguish the pyrolysis front, it corresponds to the white-black interface located at about x = 5 m. Figure 6 shows the time evolution of the fire-front positions for duly chosen simulations; the ROS was obtained by evaluating the average slopes of the curves in Figure 6 after t = 10 s (end of ignition time). We notice, as expected, that increasing the wind speed or decreasing the fuelbed moisture-content increases the rate of fire spread.

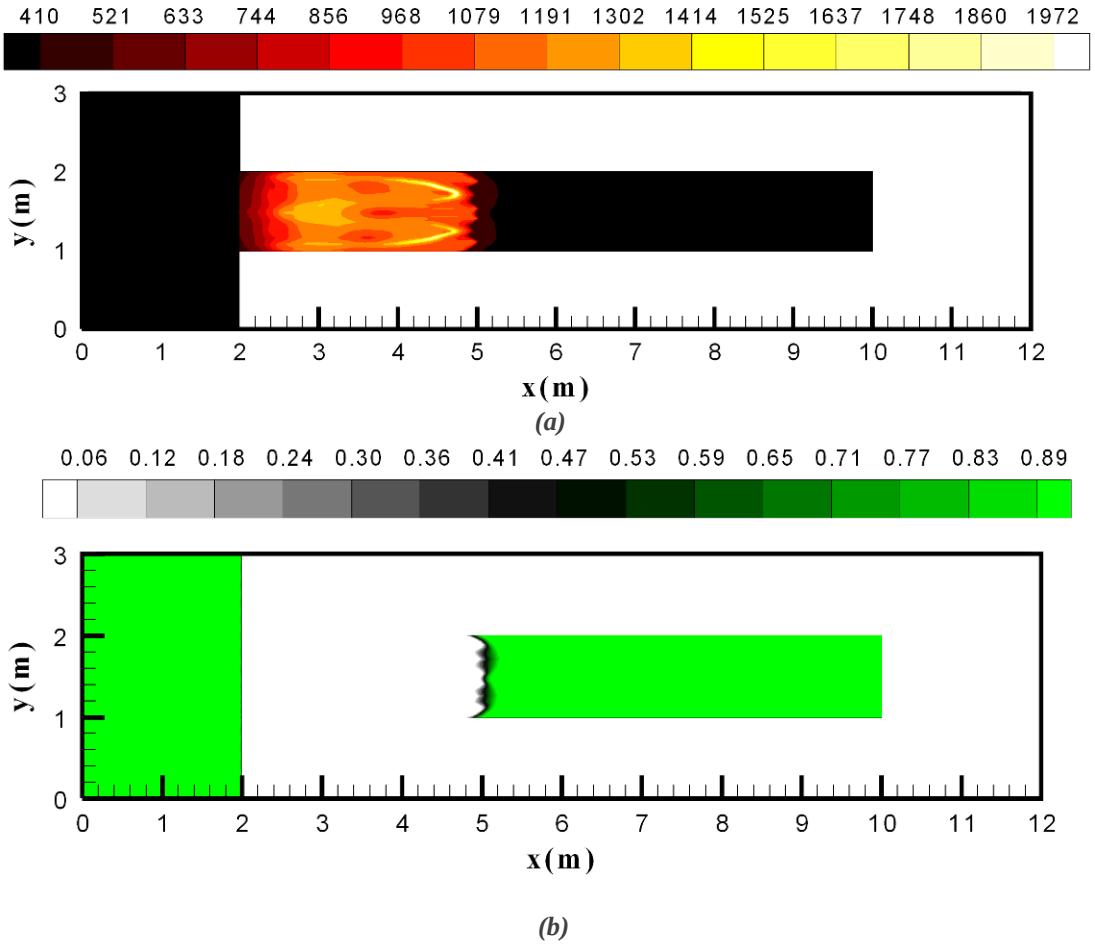

Figure 3. Temperature (a) and dry material fraction (b) distributions at fuelbed-surface (z = 0.203 m) obtained at t = 15 s, corresponding to experiment EXMC23 of Catchpole et al. (regular excelsior, wind speed of U = 2.68 m/s, moister content 5.5%, see Tab. 1 for more details).

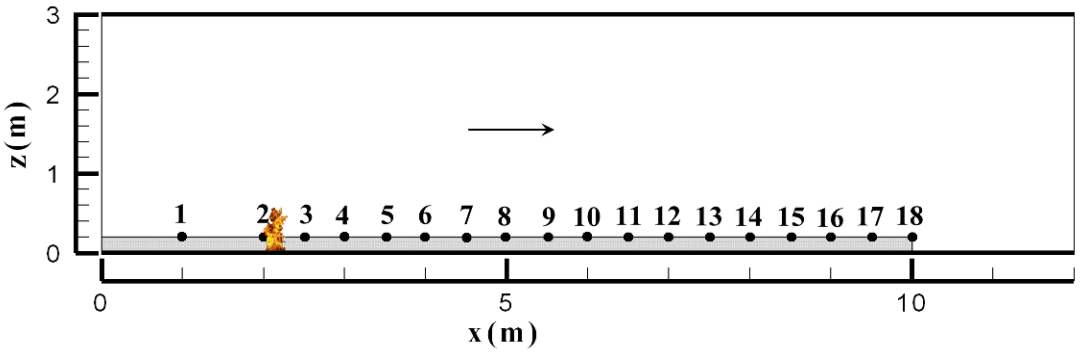

Figure 4. Positions in the vertical median plan of the computation domain (at y = 1.5 m) where fuelbed characteristics are monitored during simulation.

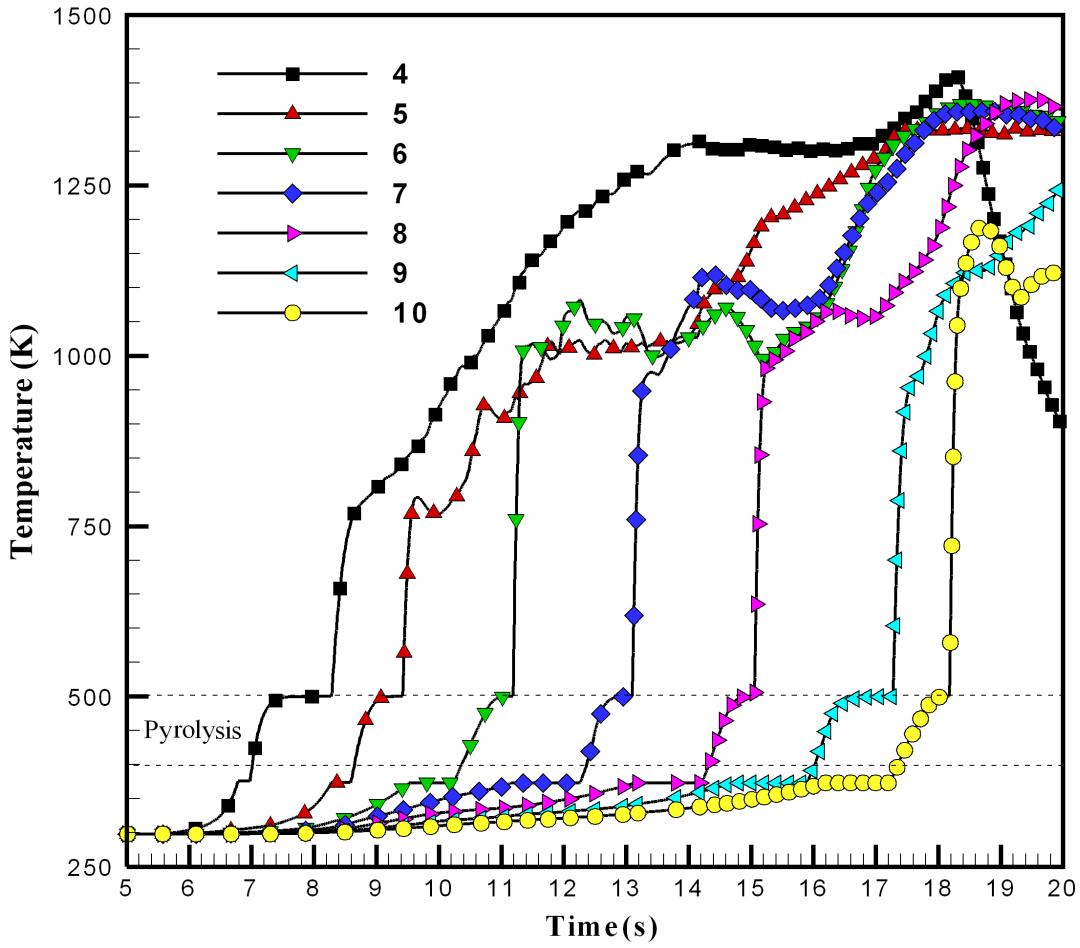

Figure 5. Time-evolution of the fuelbed temperature at positions 4 to 10 of Figure 4, corresponding to experiment EXMC23 of Catchpole et al. (regular excelsior, wind speed of U = 2.68 m/s, moister content of 5.5%, see Tab. 1 for more details).

The rates of fire spread were evaluated for the different simulations that had been conducted and are shown in Tab. 2, compared to those obtained experimentally. Table 2 shows also ROS values obtained using the correlation given by eq. (2) that was established by Catchpole *et al*. for different fuel types and properties using 357 experimental fires.

$$ROS = \frac{\left(I + mU^{n}\right)e^{-347/\sigma}\alpha^{-0.499}e^{-kM}}{\rho_{P}\left(Q_{P} + MQ_{W}\right)} \qquad (2)$$

Where I = 495.5, m = 1934, n = 0.91, and k = – 0.73 are model constants, and Q_P = 711 KJ/Kg and Q_W = 2250 KJ/Kg are the pyrolysis heat and water latent heat respectively.

We notice first that "FireStar3D" predicts the correct order of magnitude of the rate of fire spread (which is not easy to obtain for confined fires) and its correct dependence on the wind speed and on the fuelbed moisture-content. We notice also that, even though FireStrar3D seems to overestimate the rate of fire spread in the case of Rothermel configuration, especially for low wind speeds (EXMC24), the predicted ROS values are comparable to those obtained experimentally or estimated using different analytical models.

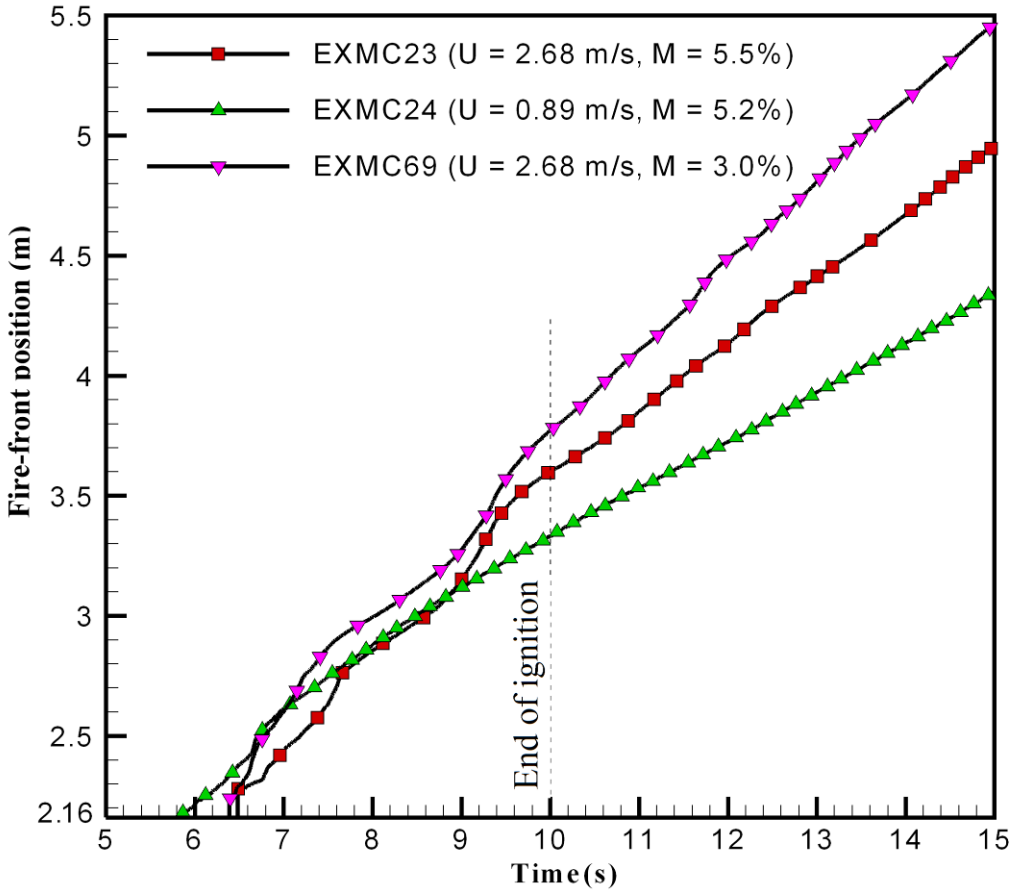

Figure 6. Time-evolution of the average position of the pyrolysis front, corresponding to experiment EXMC23, EXMC24, and EXMC69 of Catchpole et al., showing the effect of wind speed and moisture content on the rate of fire spread. The ROS is the average slope of the curve after t = 10 s (end of ignition time).

Table 2. Comparison of the rates of spread (in m/s) obtained numerically using FireStar3D, experimentally, and using the correlation established in Catchpole et al. (eq. 2) for the different experiments shown in Tab. 1.

	EXMC23	EXMC24	EXMC28	EXMC36	EXMC48	EXMC69
Simulation	0.285	0.201	0.241	0.230	0.199	0.345
Experiment	0.252	0.105	0.129	0.156	0.175	0.242
Correlation	0.221	0.094	0.159	0.203	0.181	0.232

5. Conclusions

A fully-physical wildfire model was used to simulate a confined fire in a wind tunnel. A preliminary study was carried out in the case of a homogeneous fuel bed to evaluate the potential of the model to predict fire behaviour. The obtained result were analysed in terms of fire front rate of spread (ROS) and shape, for different wind velocities and fuel moisture content values and compared with experimental data from the literature (measurements and empirical correlations). Globally, the obtained results compare well enough to experimental data, despite the relative difficulty of the considered configuration (confinement effects) and a consistent monotonicity is observed numerically

when varying the control parameters (wind speed and moisture content) accordingly to the realistic physical expectations. The next step will be to extend the investigation to other set of parameters (influence of particle size, other fuel types, …) and also to consider heterogeneous fuelbeds in this confined configuration for which correlations also exist. Finally and beyond the scope of this work, prospective numerical simulations for grassland fires were also carried out for different values of wind velocities; the leading results are in good agreement with some previous numerical studies and experimental data from literature.

6. Acknowledgements

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7. References

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