



HAL
open science

Numerical simulation of grassland fires behavior using an implicit physical multiphase model

Nicolas Frangieh, Dominique Morvan, Sofiane Meradji, Gilbert Accary, Oleg
Bessonov

► **To cite this version:**

Nicolas Frangieh, Dominique Morvan, Sofiane Meradji, Gilbert Accary, Oleg Bessonov. Numerical simulation of grassland fires behavior using an implicit physical multiphase model. *Fire Safety Journal*, 2018, 102, pp.37-47. 10.1016/j.firesaf.2018.06.004 . hal-02114073

HAL Id: hal-02114073

<https://amu.hal.science/hal-02114073v1>

Submitted on 29 Apr 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Accepted Manuscript

Numerical Simulation of Grassland Fires Behavior Using an Implicit Physical Multiphase Model

N. Frangieh, D. Morvan, S. Meradji, G. Accary, O. Bessonov



PII: S0379-7112(18)30037-7
DOI: 10.1016/j.firesaf.2018.06.004
Reference: FISJ 2718
To appear in: *Fire Safety Journal*
Received Date: 29 January 2018
Accepted Date: 18 June 2018

Please cite this article as: N. Frangieh, D. Morvan, S. Meradji, G. Accary, O. Bessonov, Numerical Simulation of Grassland Fires Behavior Using an Implicit Physical Multiphase Model, *Fire Safety Journal* (2018), doi: 10.1016/j.firesaf.2018.06.004

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Numerical Simulation of Grassland Fires Behavior Using an Implicit Physical Multiphase Model

N. Frangieh¹, D. Morvan^{1,*}, S. Meradji², G. Accary³, O. Bessonov⁴

¹ Aix-Marseille Université, CNRS, Centrale Marseille, M2P2, Marseille, France

² IMATH laboratory, EA 2134, Toulon University, France

³ Scientific Research Center in Engineering, Lebanese University, Lebanon

⁵ Institute for Problems in Mechanics, Russian Academy of Sciences, Russia

(*) Corresponding author (dominique.morvan@uni-amu.fr)

Abstract

This study reports 3D numerical simulations of the ignition and the propagation of grassland fires. The mathematical model is based on a multiphase formulation and on a homogenization approach that consists in averaging the conservation equations (mass, momentum, energy ...) governing the evolution of variables representing the state of the vegetation/atmosphere system, inside a control volume containing both the solid-vegetation phase and the surrounding gaseous phase. This preliminary operation results in the introduction of source/sink additional terms representing the interaction between the gaseous phase and the solid-fuel particles. This study was conducted at large scale in grassland because it represents the scale at which the behavior of the fire front presents most similarities with full scale wildfires and also because of the existence of a large number of relatively well controlled experiments performed in Australia and in the United States. The simulations were performed for a tall grass, on a flat terrain, and for six values of the 10-m open wind speed ranged between 1 and 12 m/s. The results are in fairly good agreement with experimental data, with the predictions of operational empirical and semi-empirical models, such as the McArthur model (MK5) in Australia and the Rothmel model (BEHAVE) in USA, as well as with the predictions of other fully 3D physical fire models (FIRETEC and WFDS). The comparison with the literature was mainly based on the estimation of the rate of fire spread (ROS) and of the fire intensity, as well as on the analysis of the fire-front shape.

Keywords: Grassland fires, fire modeling, turbulent reactive flows, numerical simulation, high performance computing.

1. Introduction

Wildfire can be considered as a natural disaster or a necessary perturbation in the life of an ecosystem, depending on the place where this event occurs and on its intensity. The frontier between these two points of view depends strongly on the impact of this event on the environment and the economy, as well as on the management and the land use between natural and urban areas[1]. The ecologists often consider that the existence of low intense fires in natural areas (such as the national parks) is necessary to maintain locally the biodiversity, whereas many citizens can consider them as an unsupportable degradation of the environment, assimilated here as a recreation area. The fire regime, defined by integrating a set of characteristic parameters of fires (patterns, intensity, and frequency) for which an ecosystem presents an optimum resilience, is a good indicator of the level of perturbation caused by external factors such as climate changes or the level

46 of anthropization [2]. Various factors have in the past and can in the future, cause great
47 modifications in the fire regime in a local area, such as the European settlement in
48 America, in Australia, and in other parts of the world, the rural exodus, and global
49 warming [3]. These changes can be particularly dramatic, when very intense fires occur
50 in the wildland-urban interface (WUI) as it happened in Victoria state in Australia in 2009
51 (Black Saturday) [4] and more recently in 2016 in Alberta (Canada) near the city of Fort
52 McMurray. To have an idea of the level of destruction of such “natural” hazard (a lot of
53 fire ignitions have human caused), one of the fires occurring during the “Black Saturday”
54 event (the Kilmore East fire), had burnt more than 125 000 ha of forest, tree plantations
55 and shrubs (100 000 ha in less than 12 hours), had caused 232 casualties (and 119
56 injuries), and had destroyed 1242 houses [4,5]. The fireline intensity was evaluated to
57 88 000 kW/m (in comparison, the average power of a unit in a nuclear power plant is
58 about 1500 MW) [3].

59 Due to the extreme complexity of the problem, most of operational tools predicting
60 wildfires behavior (such as PHOENIX [6] in Australia and FARSITE in USA [7]) are based
61 on statistical or semi-empirical approaches, namely the MacArthur MK5 model [8,9] in
62 Australia and the Rothermel model (BEHAVE) in USA [10]. However, in many situations,
63 especially that deviate from the conditions on which these models were calibrated, the
64 quality of the predictions compared to real observations collected on well documented
65 fire can be qualified as poor [11]. These tools propose to evaluate some characteristic
66 parameters of fire, such as the rate of spread (ROS), the fire intensity, and the flame
67 height. However, the validity of the predictions of empirical models are limited to the
68 range of parameters used to develop the statistical laws. As for semi-empirical models,
69 such as BEHAVE, predictions at large scale are of poor quality because most of them are
70 made by extrapolation of data obtained from small-scale fires performed in a wind tunnel
71 through homogeneous dead fuel bed (pine needles, excelsior, sticks) [11], which may lead
72 sometimes to unexpected results such as a ROS greater than the wind speed. Such
73 behavior cannot be explained physically, except in the case of no wind fires or in the
74 absence of propagation mechanisms other than heat transfer by convection and radiation
75 between the flame front and the vegetation (by spot particles for example), because the
76 sum of characteristic times associated with the physical process necessary for the
77 propagation of the fire (drying, pyrolysis, combustion ...) is larger than the travel time
78 characterizing the wind flow. Consequently, other approaches have been proposed to
79 improve the knowledge of the physical process responsible of the fire behavior. These
80 alternative class of fire models are based on more or less realistic description of the
81 physical phenomena governing the heat transfer between the fire front and the
82 vegetation [12]. A fully physical model addresses the problem of fire spread by analyzing
83 its behavior through its physicochemical aspects [13,14]. This approach minimizes the
84 need of using an empirical parameterization, even if, compared to empirical and semi-
85 empirical models, it needs bigger computational resources (which limit their capability
86 in solving the problem in real time), it is also more promising in the understanding of the
87 physics of fires [11, 15–18]. The fully physical approach has also a great potential in the
88 management of fire hazard in wildland urban interfaces, using an engineering approach,
89 such as the dimensioning of a fuel break, the evaluation of heat flux on a target located
90 inside the WUI, the interaction between two fire fronts [19–22].

91 The 3D model described in this work is based on a multiphase formulation and solves the
92 conservation equations of the coupled system formed by the vegetation and the
93 surrounding gaseous medium [13,18,23]. The model takes into account the vegetation

94 degradation processes (drying, pyrolysis, and combustion), the interaction between the
95 atmospheric boundary layer and vegetation (aerodynamic drag, heat transfer by
96 convection and radiation, and mass transfer), and the transport in the gaseous phase
97 (convection, turbulence, and combustion). The model is implemented in a modular and
98 parallelized 3D computation code referred to as "FireStar3D". The code is based on a
99 finite volume discretization of the governing transport equations (3rd order in time and
100 2nd order in space) and has undergone numerous validations [23–26]. The predictive
101 potential of FireStar3D model was tested at a small scale in the case of litter fires (fire
102 propagation through a homogeneous fuelbed in a wind tunnel) [23]. The objective of this
103 study is to extend the tests at a larger scale for grassland fires. Grassfires have the great
104 advantage to have been extensively studied experimentally, in very good conditions,
105 especially the experimental campaigns carried out in Australia [27–29], which are
106 considered as a good benchmark to test wildfire physical models [15,16,30]. For different
107 wind speeds, fire behavior and spread through homogeneous grassland is analyzed in
108 terms of rate of fire spread, fire intensity, and shape of the fire front. The results were
109 compared with data collected during experimental campaigns and predictions from semi-
110 empirical and other physical models.

111 2. Modeling and Numerical Method

112 The mathematical model is based on a multiphase formulation, it consists in a first step
113 of averaging the conservation equations (mass, momentum, energy ...) governing the
114 behavior of the coupled system formed by the vegetation and the surrounding
115 atmosphere inside elementary control volumes including both the solid phase (the
116 vegetation) and the gaseous phase. This first operation, similar to a homogenization step,
117 results in the introduction of source/sink terms on the right hand side of the equations,
118 representing the contributions of the interaction terms (exchanges of mass, drag, heat
119 flux ...) between the gaseous phase and the vegetation. The details of the model have been
120 widely presented in previous publications, we invite the reader to consult references
121 [13,14,17,18,30] for more information.

122 The model consists of two parts that are solved on two distinct grids. The first part
123 consists of the equations of a reacting turbulent flow in the gaseous phase composed as a
124 mixture of fresh air with the gaseous products resulting from the degradation of the solid
125 phase (by drying, pyrolysis, and heterogeneous combustion) and the homogeneous
126 combustion in the flaming zone. The second part consists of the equations governing the
127 state and the composition of the solid phase subjected to an intense heat flux coming from
128 the flaming zone.

129 Solving the gaseous phase model consists in the resolution of conservation equations of
130 mass, momentum, energy (in enthalpy formulation), and chemical species (O₂, N₂, CO,
131 CO₂, and H₂O) filtered using an unsteady RANS approach (TRANS) with Favre average
132 formulation [31]. The closure of the averaged conservation equations are based on the
133 concept of eddy viscosity [32] obtained from an evaluation of the turbulent kinetic energy
134 k and its dissipation rate ε . A high Reynolds number version of a two-equation statistical
135 turbulence model (k - ε) is used with the RNG formalism [33,34]. The temperature
136 dependence of the gas-mixture enthalpy is based on CHEMKIN thermodynamic tables
137 [35]. A combustion model based on Eddy Dissipation Concept (EDC) [32,36] is used to
138 evaluate the combustion rate occurring in the gaseous phase. Finally, because radiation
139 heat transfer (mainly due to the presence of soot particles in the flame) plays an
140 important role for the propagation of the fire front, the field of soot volume-fraction in

141 the gas mixture is calculated by solving a transport equation [37,38] including a
142 thermophoretic contribution in the convective term and taking into consideration soot
143 oxidation [39].

144 Concerning the solid phase model, during the thermal degradation, the composition of
145 the solid fuel particles representing the vegetation is represented as a mixture of dry
146 material (generic term for a mixing of cellulose, hemicellulose, and lignin), charcoal,
147 moisture, and residual ashes. For each solid particle, the model consists in solving the
148 equations governing the time evolutions of the mass fractions of water, of dry material,
149 of charcoal, as well as of the total mass of the solid particle, its volume fraction and its
150 temperature (the model does not assume a thermodynamics equilibrium between the gas
151 mixture and solid fuel particles). The degradation of the vegetation is governed by three
152 temperature-dependent mechanisms: drying, pyrolysis, and charcoal combustion. The
153 pyrolysis process starts once the drying process is completed and charcoal combustion
154 starts once the pyrolysis process is achieved. The constants of the model associated with
155 the charcoal combustion (activation energy and pre-exponential factor) are evaluated
156 empirically from a thermal analysis conducted on various solid fuels samples [13,40].

157 The interaction between the gaseous phase and the solid one is taken into account
158 through coupling terms that appear in both parts of the model. The coupling in the
159 momentum and turbulence equations is obtained by adding aerodynamic drag terms.
160 These terms (both source and sink) are proportional to V (for turbulence destruction), to
161 V^2 (for the momentum equation), and to V^3 (for turbulence production), where V is the
162 local average of the velocity magnitude [30], and include a drag coefficient (evaluated
163 empirically) multiplied by a reference surface, defined here as the Leaf Area Density
164 (LAD). Heat transfer between the gas mixture and the solid fuel is based on empirical
165 correlations for convective transfer coefficient [40], and on the resolution of the radiative
166 transfer equation [41] that accounts for the presence of soot in the flaming zone and for
167 the presence of hot particles in the vegetation layer (embers) [13]. Finally, mass transfer
168 from the solid phase to the gaseous phase is represented by adding source/sink terms in
169 the mass conservation equations of both phases.

170 The balance equations in the gaseous phase are solved numerically using a fully implicit
171 finite volume method in a segregated formulation [42]. "FireStar3D" model predicts
172 turbulent reacting flows in rectangular domains using a structured but non-uniform
173 staggered mesh. Time discretization relies on a third order Euler scheme with variable
174 time stepping strategy. To ensure numerical stability, space discretization is based on
175 second order schemes with flux limiters (QUICK scheme [43,44]) for convective terms
176 while diffusion terms are approached by central difference approximation with deferred
177 corrections [45] to maintain the second order accuracy in space. The Radiative Transport
178 Equation (RTE) is solved using a Discrete Ordinate Method (DOM), consisting in solving
179 the radiation-intensity equation in a finite number of directions [46]. The radiative
180 transfer equation accounts for gas-soot mixture absorption of radiative intensity
181 depending on the amounts of combustion products (CO_2 and H_2O), on the gas mixture
182 temperature, and of the soot volume fraction [47]. This set of discrete contributions is
183 then integrated using a numerical Gaussian quadrature rule (a S8 method is used) for the
184 calculation of the total irradiance. The set of ordinary differential equations describing
185 the time evolution of solid-fuel state (mass, temperature, and composition) are solved
186 separately using a fourth order Runge-Kutta method. From implementation point of view,
187 the computation code is parallelized [48] and optimized [49] using OpenMP directives
188 (operational on shared memory platforms and on Intel Xeon Phi coprocessors). Finally,

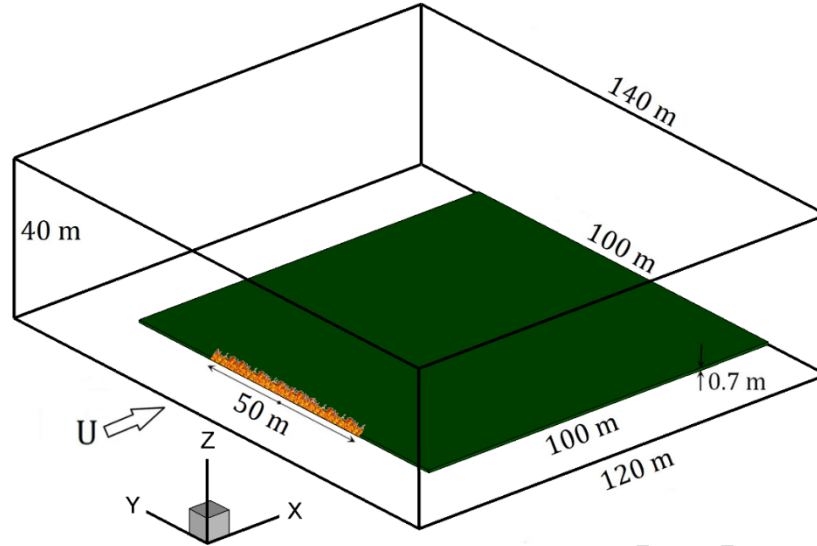
189 the hydrodynamic module of the code has been extensively validated on several
 190 benchmarks of laminar and turbulent natural convection, forced convection, and
 191 neutrally stratified flow within and above a sparse forest canopy [48–50].

192 Compared to the two main physical wildfire models referenced in the literature, i.e. WFDS
 193 [15] and FIRETEC [16], FireStar3D shares many similitudes with WFDS but it also
 194 presents important differences. In FireStar3D, as in WFDS, the flow solver is based on a
 195 low Mach number formulation, a real calculation of the turbulent combustion in the flame
 196 (using Eddy Dissipation Concept model), which is not the case in FIRETEC [30]. From a
 197 numerical point of view, FireStar3D is fully implicit whereas the solver in WFDS is
 198 explicit. One of the main differences at the modeling level with WFDS is related to the
 199 estimation of the radiation heat transfer from the flame. In WFDS, the radiative heat
 200 transfer is calculated but a minimum threshold value is fixed as a minimum radiative ratio
 201 from the energy released from homogeneous combustion; this arbitrary approach was
 202 not introduced in FireStar3D. These two characteristics, constitutes an important
 203 progress toward a more physical wildfire model, it represents also a great challenge in
 204 terms of computational resources.

205 3. Grassland Fire Configuration

206 As mentioned in introduction, the aim of this work is to show that the model is able to
 207 predict numerically the spread of a fire through grassland. A perspective view of the
 208 domain is shown in Fig. 1; the computational domain was 120 m long, 140 m wide, and
 209 40 m high. The homogeneous vegetation layer, of height $\delta = 0.7$ m, is 100 m long and 100
 210 m wide, and it is located at 20 m from the domain inlet and at 20 m from the domain
 211 lateral boundaries. The main physical characteristics of the vegetation layer are given in
 212 Tab. 1. The heat yield of the fuel is 18000 kJ/kg, the solid fuel particles are assumed to
 213 behave as a black body, and a vegetation family of cylindrical shape was considered. The
 214 shape of the fuel particles is used for the description of their regression law and for the
 215 estimation of the heat transfer coefficient. For the solid phase, a uniform grid with $(\Delta x,$
 216 $\Delta y, \Delta z) = (0.25 \text{ m}, 0.25 \text{ m}, 0.035 \text{ m})$ was used matching the vegetation zone, while a non-
 217 uniform grid of $224 \times 248 \times 90$ cells was used for the fluid phase covering the whole
 218 computational domain. Within the vegetation zone, the fluid-phase grid was uniform with
 219 $(\Delta x, \Delta y, \Delta z) = (0.5 \text{ m}, 0.5 \text{ m}, 0.07 \text{ m})$ and then it was coarsened gradually toward the open
 220 boundaries according to a geometric progression with common ratio 1.05. Both the solid-
 221 phase and the fluid-phase grids were characterized by cells sizes below the extinction
 222 length scale [14] within the vegetation given by $4/\alpha\sigma$ and equal to 0.5 m in our case. This
 223 value should not be exceeded in order to avoid fire extinction especially in the case
 224 radiation-dominated fire propagation (i.e. when the wind speed is low to moderate).
 225 Furthermore, in the context of using a high Reynolds number turbulence model, the
 226 choice of the mesh size at the vicinity of solid bottom wall is strongly related to the quality
 227 of the obtained solution. The dimensionless distance to the wall z^+ is defined by Eq. 1
 228 where $C_\mu = 0.0845$, k is the turbulent kinetic energy, and ρ and μ respectively the density
 229 and the dynamic viscosity of gas mixture. The center of any cell adjacent to the bottom
 230 wall must have a dimensionless distance to the wall that satisfies the constraint
 231 $11.5 < z^+ < 500$ [44] (i.e. the cell center lies within the fully turbulent zone), and this
 232 during the entire simulation time.

$$233 \quad z^+ = \frac{\rho C_\mu^{1/4} k^{1/2} z}{\mu} \quad (1)$$



234

235 **Figure 1.** Perspective view showing the dimensions of the computational domain and of
 236 the vegetation cover. The ignition line is 2 m wide and 50 m long. In the non-uniform
 237 ignition mode, the burner is activated from the middle of the ignition line toward its ends
 238 at the speed of 1 m/s.

239

240 Burner activation occurs at time $t = 10$ s, time for which the flow had reached a
 241 statistically-steady state, this phase was considered for the entire cases studied in this
 242 paper. During this (purely dynamic) flow settlement phase, homogeneous Neumann
 243 boundary conditions were imposed at the open boundaries of the computational domain
 244 for all primary variables of the problem excepted for y and z -velocity components where
 245 Dirichlet conditions (value set to zero) were imposed. In addition, a negative pressure
 246 gradient is applied in the wind direction (Ox); this pressure gradient was automatically
 247 adjusted during the flow settlement phase to obtain the desired level of the 10-m open
 248 wind speed. This procedure allowed collecting the turbulent fields at the open
 249 boundaries, and these fields were then used during the burning phase, in particular for
 250 the management of the entering turbulent fluxes.

251

Vegetation height δ (m)	Solid-fuel volume-fraction α	Surface/Volume ratio σ (m^{-1})	Dry material density ρ (kg/m^3)	Moisture content M (%)	Heat yield (kJ/kg)	Thermal emissivity	Vegetation family shape
0.7	0.002	4000	500	5	18000	1	Cylindrical

252

Table 1. Geometric and physical properties of the grassland vegetation [16,30]

253

254 At time $t = 10$ s, the burner was activated along an ignition line, extends over $w = 50$ m of
 255 length and 2 m of wide, as shown in Fig. 1. Fire was set by injecting CO gas at 1600 K in
 256 the burning zone from the bottom boundary of the domain. At time $t = 10$ s, the average
 257 velocity V_{inj} of CO was maximum (equal to 0.1 m/s), and then it was decreased linearly
 258 with the consumed mass of solid-fuel according to equation (2). This procedure avoided
 259 destabilizing the flame front by abruptly ceasing the CO injection and avoided any
 260 excessive external energy input.

$$261 \quad V_{inj} = \left(1 - \frac{m_b}{m_{b0}}\right) \times (0.1 \text{ m/s}) \quad (2)$$

262 In Eq. 2, m_{b0} represented the mass of dry material initially available above the burner area
 263 (i.e. the mass of dry material contained in the volume $V_{b0} = 2 \times 50 \times \delta \text{ m}^3$). Equation 2 was
 264 used between $t = 10 \text{ s}$ and $t = 35 \text{ s}$ (i.e. during 25 s) as long as V_{inj} remained positive and
 265 CO injection ceased if V_{inj} reached zero during this time interval.

266
 267 The parametric study focused on the influence of 10-m open wind speed on the fire
 268 behavior in terms of rate of spread, of fire intensity, and of shape of the fire front. The
 269 simulations were carried out for six values of the 10-m open wind speed: 1, 3, 5, 8, 10,
 270 and 12 m/s. These velocities were measured at the domain inlet, 10 m above ground. Two
 271 modes of fire ignition were considered: uniform and non-uniform, for the entire range of
 272 the wind speed U . In the uniform ignition mode, the burner was activated at the same
 273 time throughout the ignition zone. In the case of non-uniform ignition, the burner was
 274 activated from the middle of the ignition line (at $y = 70 \text{ m}$) toward its two end sides (at y
 275 $= 70 \pm 25 \text{ m}$) at the speed of 1 m/s.

276
 277 The results presented in this study were obtained using a variable time step strategy
 278 based on the truncation-error control, with time step values varying between 0.001 s and
 279 0.01 s. At each time step, the solution is assumed to be obtained when the residuals of all
 280 conservation equations had reached 10^{-4} in normalized form. As a rough estimation of
 281 the computational cost, the simulation of 1s of fire propagation required about 7h of CPU
 282 time on a 28-cores node.

283 **4. Numerical Results**

284 This numerical study focuses on fire spread through a grassland whose vegetation
 285 structure is quite homogeneous (see Fig. 2) and identical to a natural undisturbed
 286 grassland. The simulations were carried out under conditions similar to those of the
 287 Australian experimental campaign of 1986 [27–29]. The chosen configuration is very
 288 similar to experiment C064 of controlled fire conducted by Cheney et al. (1986) on a
 289 parcel of carefully cut grass [28] and shown in Fig. 3. However, the simulations were
 290 carried out for tall grass ($\delta = 0.7 \text{ m}$) unlike experiment C064 ($\delta = 0.21 \text{ m}$); this choice was
 291 mainly motivated by the existence of prior numerical studies [16,30]. In order to assess
 292 the predictive potential of the model, the results were compared to the predictions of the
 293 Australian empirical model MK5 [51], of the US semi-empirical model BEHAVE [52], of
 294 three-dimensional physical models (FIRETEC from LANL and WFDS from NIST), and of a
 295 two-dimensional physical model (FireStar2D [30]) that solved the problem of fire spread
 296 in a vertical plane perpendicular to an infinite ignition line.



Figure 2. Structure of the grassland vegetation (tall-grass) (from https://commons.wikimedia.org/wiki/File:Dry_Grass.JPG)

297
298
299
300

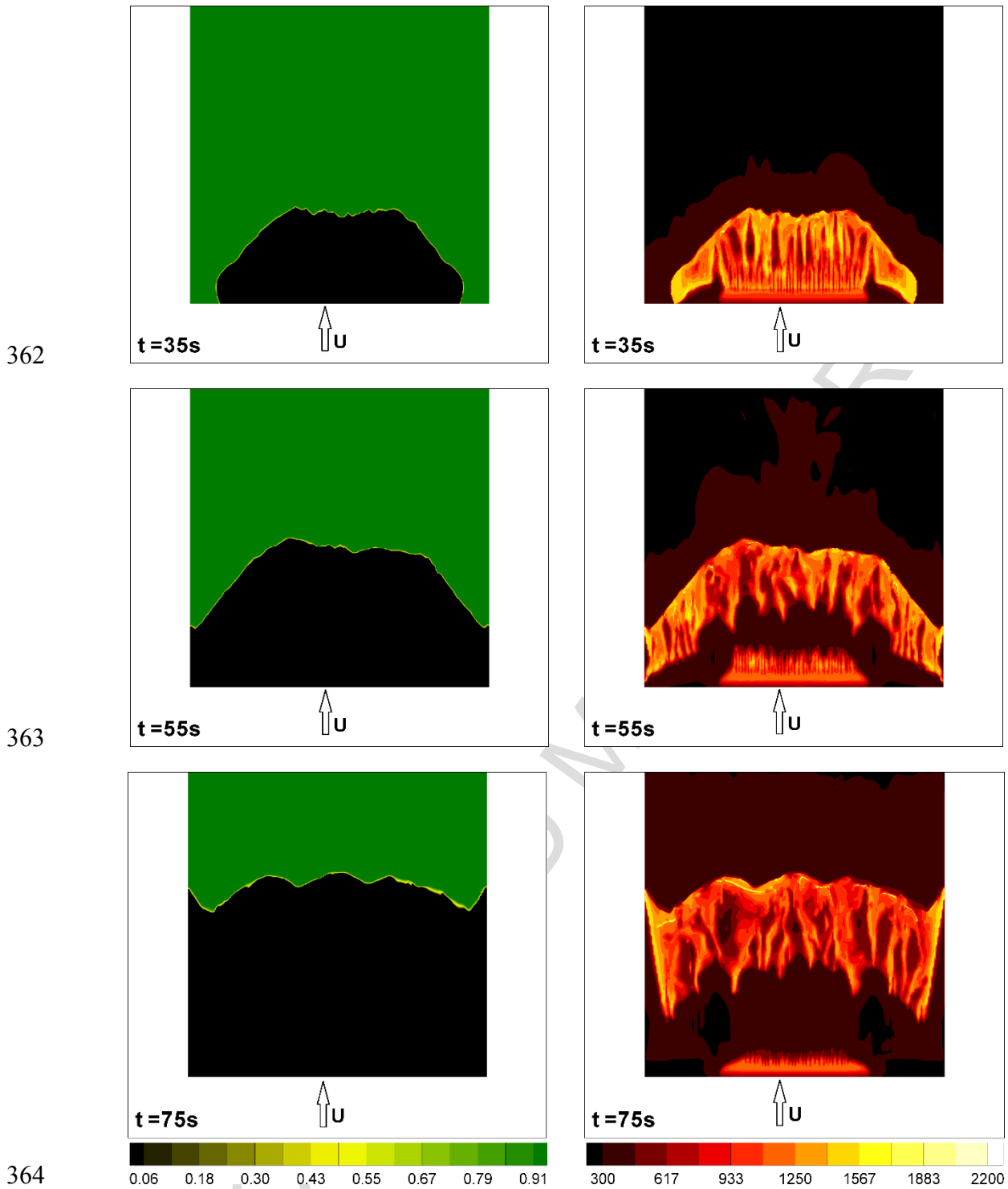


301
302 **Figure 3.** Photos of experiment 'C064 - AU Grassland Fire' carried out by Cheney et al.
303 [28], 27s (left) and 53s (right) after fire ignition starts. Vegetation layer height $\delta = 0.21\text{m}$,
304 fuel load $\alpha\rho\delta = 0.28\text{ kg/m}^2$, fuel surface/volume ratio $\sigma = 9770\text{ m}^{-1}$, moisture content M
305 $= 6.3\%$, ignition-line length $w = 50\text{ m}$, wind speed $U = 4.6\text{ m/s}$.
306

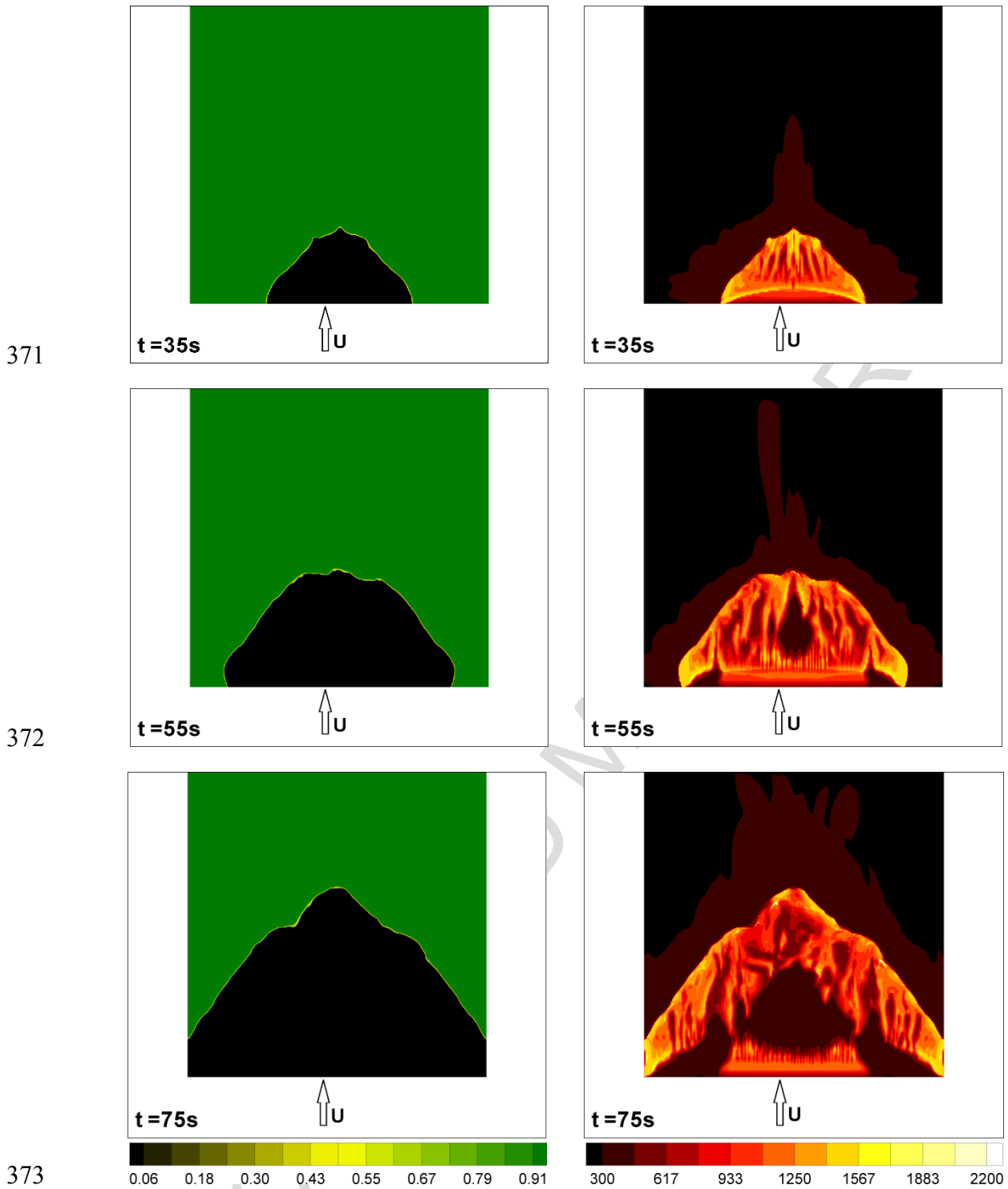
307 **4.1. Fire Regimes and Fire-Front Shape**

308 For a wind speed of 5 m/s, Fig. 4 shows a top view of the propagation of a grassland fire
309 uniformly ignited at time $t = 10\text{ s}$ (in a 2 m-wide and 50 m-long strip). Time $t = 35\text{ s}$
310 corresponds to end of ignition, unless the velocity of CO injection given by Eq. 1 had
311 reached zero before that time. The pyrolysis front used to evaluate the ROS can be clearly
312 seen on the mass fraction of the dry material. The results show: (i) the lateral fire spread
313 in addition to the propagation in the wind direction, (ii) the ripple effect on the sides of
314 the vegetation layer (visible at $t = 55\text{ s}$ and $t = 75\text{ s}$) when the pyrolysis front reaches
315 these boundaries, and this effect becomes more visible with time (with more developed

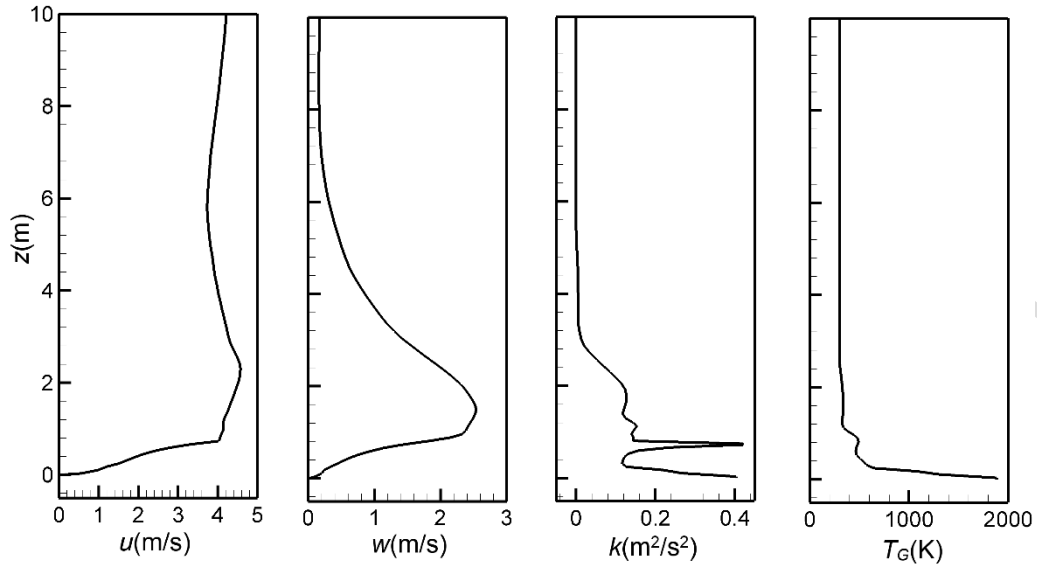
ripples), (iii) the remote heating effect due to radiation, which is responsible for the drying of the fuel prior to arrival of the fire front, and (iv) the presence of some charcoal downstream the ignition line that continues burning behind the fire front due to the screening effect of CO injection that prevents the combustion of a part of charcoal downstream the ignition line. With time, we notice that the fire front loses gradually its parabolic shape and its forward-propagation speed becomes more important at the lateral sides than at the central part of the fire front. However, the leading point of the fire front remains nevertheless at the central part during the entire simulation. This effect is not only inherent to the ignition method but also to the ratio between the length of the ignition line and the lateral extent of the vegetation cover. Decreasing significantly this ratio should reduce this effect or might suppress it completely. Figure 5 is the counterpart of Fig. 4 using the non-uniform ignition mode. The idea is to represent the ignition method of experience C064, and more generally that of the Australian experimental campaign, where fire is set by two persons using a torch starting at the middle of the ignition line and walking in opposite direction at the speed of 1 m/s. Testing this ignition mode was motivated by the investigation of the parabolic shape of the fire front observed experimentally, as shown by Fig. 3 and as confirmed by other experiments, despite the observed loss of symmetry due to a change in the wind direction [28]. Other numerical simulations obtained using the same kind of fire physical model, have exhibited similar behavior, i.e. by igniting fire instantaneously along a sufficiently long width, the fire front keep a nearly linear shape (slightly incurved toward the back) in its central part [15]. A nearly parabolic front shape could only be reproduced numerically, if the ignition was restricted to a quite small line (less than 10m) or using a dynamical ignition procedure as in this study. Figure 5 shows in this case that the pyrolysis front is qualitatively more consistent with the experimental observations. It seems however that the ROS value (evaluated from the trajectory of the heading fire) is not significantly affected by the ignition method. This was certainly due to the fact that the initial width of the ignition line (50 m) was sufficiently long to not affect much the magnitude of the rate of spread. Experimental investigations have shown that above an ignition line equal to 50 m the rate of spread of the head fire was nearly equal to the theoretical value observed for an infinitely long fire front [28]. We can notice on both simulations, that the lateral expansion of the fire front (flank fire) was correctly reproduced, this is a good indicator of the quality of the model part in charge of the radiation heat transfer between the flame and the vegetation. This behavior was also correctly reproduced by simulations performed using WFDS, whereas it was underlined as one of the major point to improve in FIRETEC [16,53]. Figure 6 shows vertical profiles of primary variables at a duly chosen location corresponding approximately to the furthestmost point of the fire front in Fig. 5 (at $t = 35$ s). The figure highlights the appropriate mesh resolution for the evaluation of the resolved-variables gradients and the production of the turbulent kinetic energy at the surface of the fuel bed. To illustrate the remote heating effect mentioned earlier, figure 7 shows that the solid-fuel temperature at the fuel-bed surface exceeds that of the gas mixture ahead of the fire front (located from the mass fraction of dry material). This means that the increase of the solid-fuel temperature is not the result convection heat transfer from the gas mixture. Consequently and as mentioned before, this remote heating can only be imputed to radiative heat transfer from the flaming zone, resulting in the water content loss observed ahead of the fire front in Fig. 7.



365 **Figure 4.** Top views of the computational domain (see Fig. 1) showing the propagation
 366 of a grassland fire in the case of a uniform fire-ignition mode (ignition at $t = 10\text{ s}$), for a
 367 10-m open wind speed $U_{10} = 5\text{ m/s}$. Left: mass fraction of dry material at vegetation height
 368 showing the shape of the pyrolysis front, right: temperature field (in Kelvin) at the surface
 369 of the solid fuel.
 370

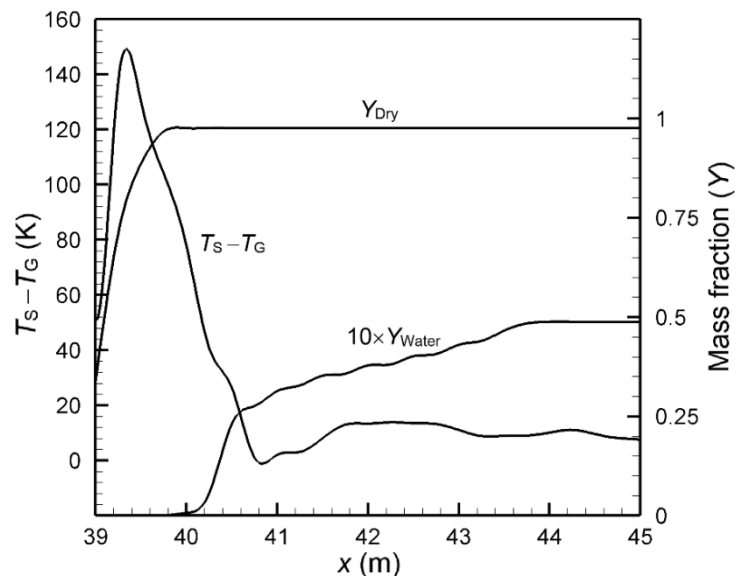


374 **Figure 5.** Top views of the computational domain (see Fig. 1) showing the propagation
 375 of a grassland fire in the case of a non-uniform fire-ignition mode (ignition at $t = 10$ s), for
 376 a 10-m open wind speed $U_{10} = 5$ m/s. Left: mass fraction of dry material at vegetation
 377 height showing the shape of the pyrolysis front, right: temperature field (in Kelvin) at the
 378 surface of the solid fuel.
 379
 380
 381



382
383
384
385
386

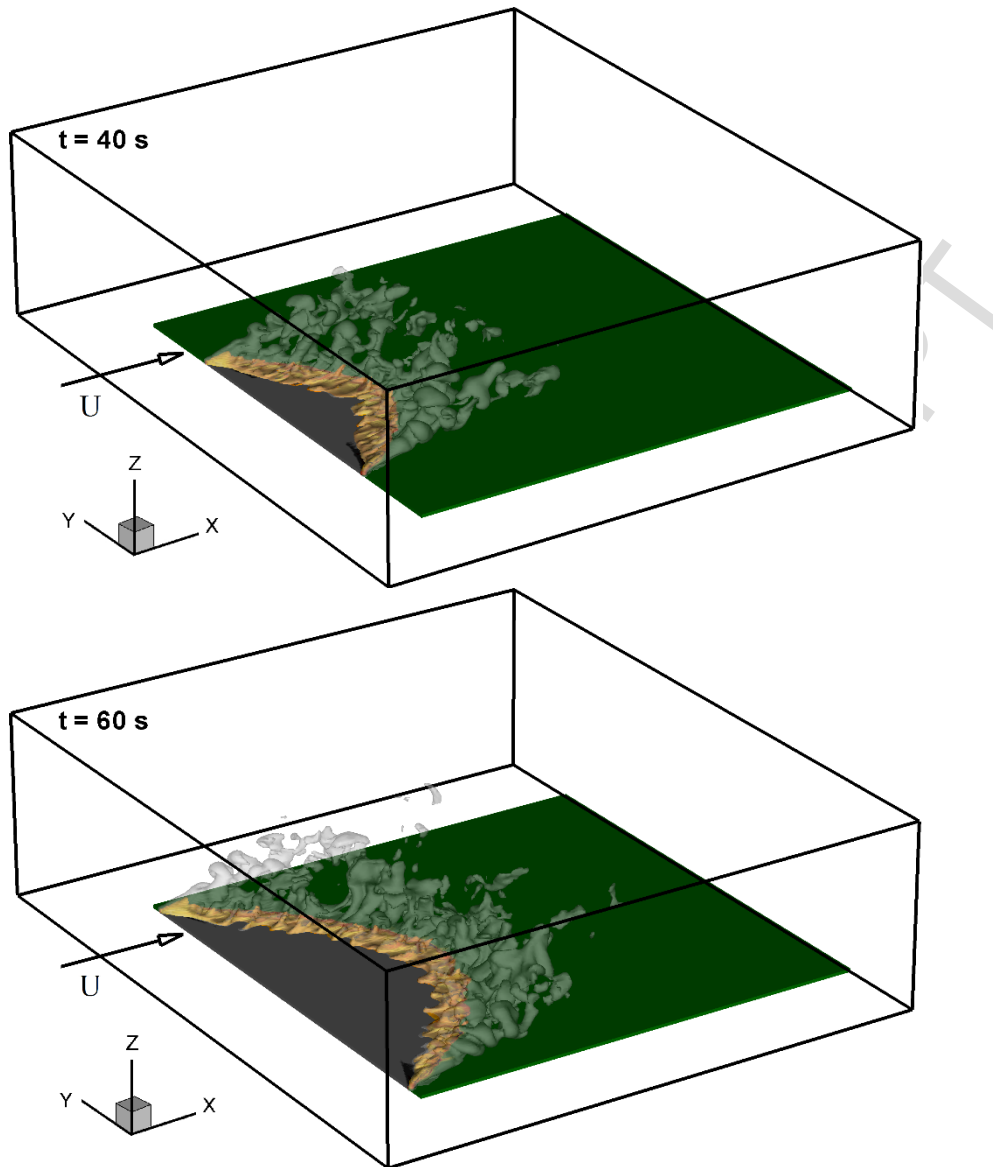
Figure 6. Vertical profiles of u and w (x and z components of the velocity), k (turbulent kinetic energy), and T_G (gas mixture temperature) obtained for $U_{10} = 5$ m/s, in the case of a non-uniform fire-ignition, at $t = 35$ s along line ($y = 70$ m, $x = 32.6$ m).



387
388
389
390
391
392
393
394
395
396
397
398
399

Figure 7. Temperature difference between the solid fuel and the gas mixture, dry material and water mass fractions along the line ($y = 70$ m and $z = \delta$) obtained at $t = 35$ s, for a 10-m open wind speed $U_{10} = 5$ m/s, in the case of a non-uniform fire-ignition mode.

3D views of the fire propagation obtained for a wind speed $U_{10} = 5$ m/s and a non-uniform ignition mode are represented in Fig. 8. These figures are taken at two characteristic times before and when the fire front had reached the side limits of the plot. These results show clearly the potential of FireStar3D in reproducing numerically (at least qualitatively) the propagation of the fire through a grassland. The model is able to reproduce the characteristic parabolic shape of the fire front associated with this type of ignition procedure (see Fig. 3) as it was mentioned in experiments on the field [15,28].



400

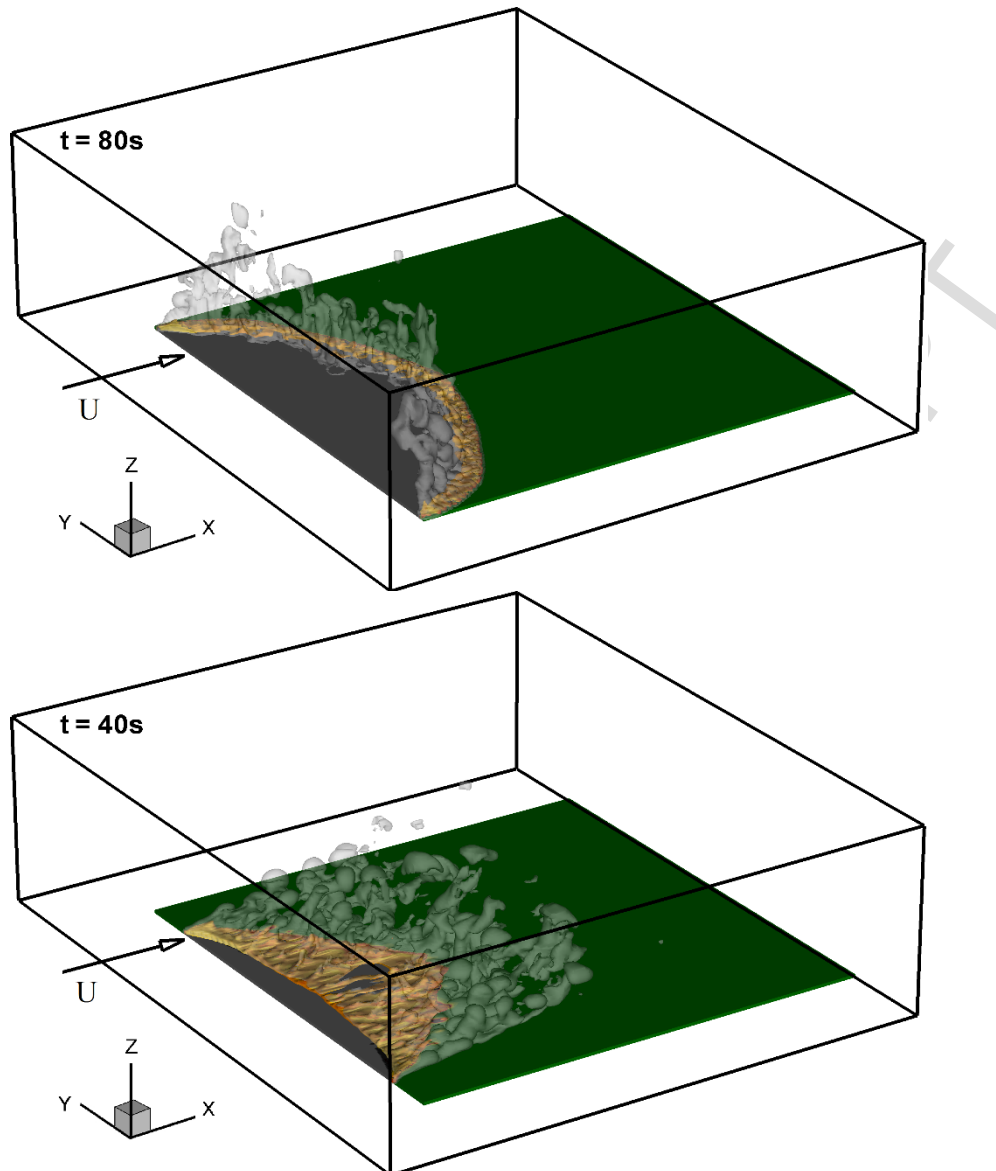
401

402 **Figure 8.** 3D View of one isovalue surface of the soot volume fraction (10^{-6}) colored by
 403 the temperature of the gas (in yellow) and one isovalue surface of the water mass fraction
 404 (10^{-3}) (in grey with 50% of transparency) for $U_{10} = 5$ m/s and at different times, showing
 405 the fire propagation in the case of non-uniform fire-ignition mode.

406

407

408 To understand the effect of the wind speed on the flame structure and more generally on
 409 the dynamic of fire, 3D views of the fire propagation obtained for two extreme wind speed
 410 $U_{10} = 1$ m/s and 10 m/s are shown in Fig. 9. It is obvious that for a small value of the wind
 411 speed ($U_{10} = 1$ m/s), the flame plumes rise is not noticeably affected by the action of the
 412 cross wind. In this case the fire front can be assimilated to an obstacle, and the air flow is
 413 deflected vertically by the plume. On the other hand, Fig. 9 shows how larger value of
 414 wind speed ($U_{10} = 10$ m/s) affects more significantly the rise of the flame plumes by
 415 crossing the fire front and pushing the hot gases toward the unburned vegetation. We can
 416 also notice that the wind speed increases significantly the depth of the fire front.



417

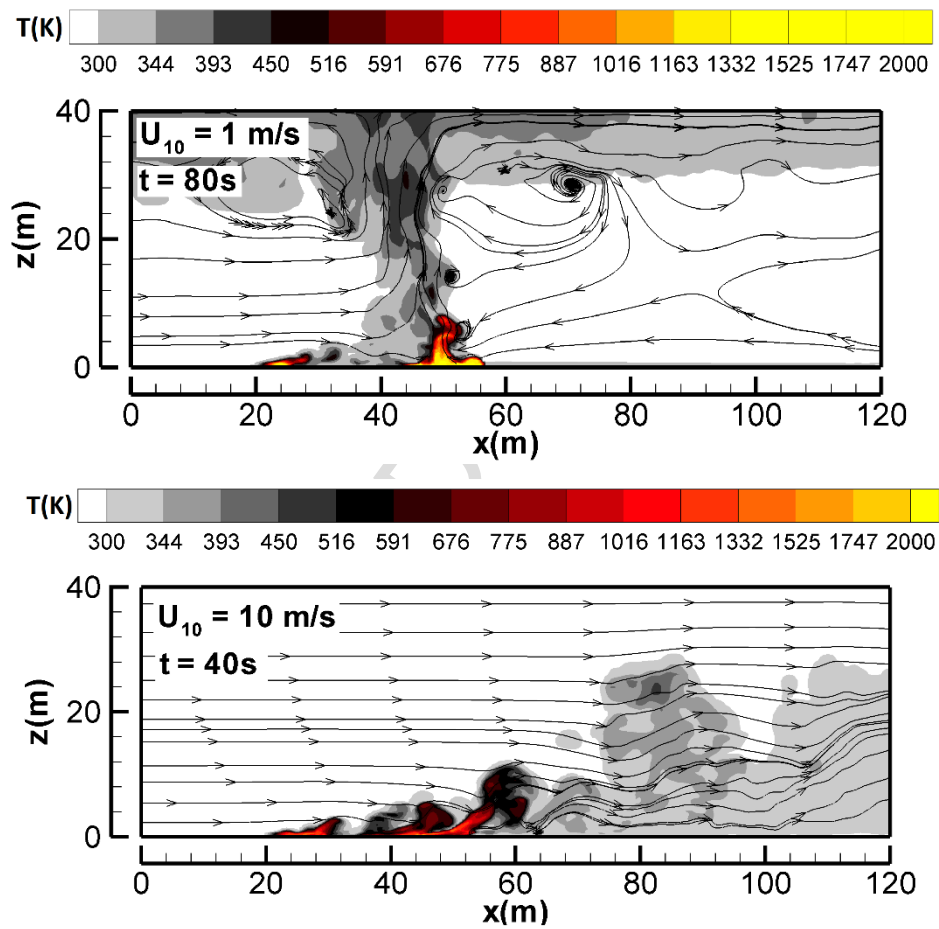
418

419 **Figure 9.** 3D View of one isovalue surface of the soot volume fraction (10^{-6}) colored by
 420 the temperature of the gas (in yellow) and one isovalue surface of the water mass fraction
 421 (10^{-3}) (in grey with 50% of transparency) for $U_{10} = 1$ m/s (top) and $U_{10} = 10$ m/s (bottom),
 422 showing the effect of wind speed on the fire dynamics in the case of non-uniform fire-
 423 ignition mode.

424

425 These phenomena are further illustrated by Fig. 10 showing cuts of the temperature and
 426 the flow fields (streamline) in the vertical median plane. For moderate wind conditions,
 427 we notice that the fresh air is sucked from the vicinity of the fire front supplying the
 428 thermal plume; the streamlines in Fig. 10 (top) show clearly the existence of aspiration
 429 regions ahead the fire front. In the literature, this regime is often referred to as “plume
 430 dominated fires”. As indicated previously, these results highlight the capability of the
 431 code to reproduce the backflow generated by the fire front on the leeward direction. In
 432 return for stronger wind conditions, the structure of the air flow is less affected by the
 433 fire front as shown in Fig. 10 (bottom), and this effect is limited to the local acceleration
 434 of the flow (resulting from a local expansion of the gas) in the plume and this regime is
 435 often referred to as “wind-driven fires”. The streamlines show clearly the possibility for

436 the inlet air flow to cross the fire front. For this interaction between the fire and the flow
 437 to be possible, the fire front must be structured vertically in peaks and troughs [54]. The
 438 reproduction of this configuration is not possible in 2D, because in 2D the fire front
 439 represents a uniform thermal barrier. This justifies the interest in analyzing the behavior
 440 of the fire using 3D simulations, even if much greater computational resources are
 441 required in this case. The interaction between the flames and the flow structures greatly
 442 affects heat transfer ahead of the fire front and, consequently fire propagation; this is
 443 clearly illustrated by Fig. 11. We notice that in the case of a “plume dominated fire” ($U =$
 444 1 m/s), radiative heat transfer prevails ahead of the fire front, indeed the temperature of
 445 the solid-fuel at the fuel-bed surface exceeds everywhere that of the gas mixture, and this
 446 temperature difference decreases uniformly with the distance from the flaming zone. In
 447 return, in the case of a “wind-driven fire” ($U = 10 \text{ m/s}$), the fluctuations of this
 448 temperature difference about zero is a clear signature of a prevailing convection heat
 449 transfer between the gas mixture and the fuel bed.
 450



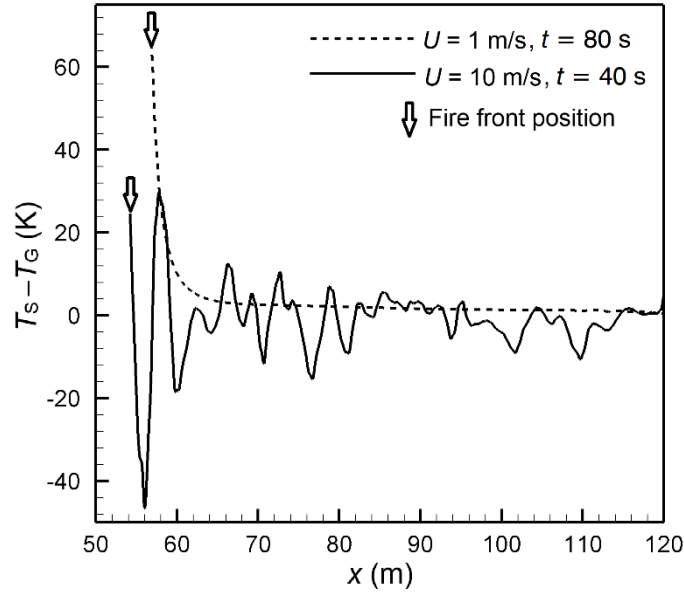
451

452

453 **Figure 10.** Temperature field and streamlines of the gaseous phase, obtained in the
 454 vertical median plane ($y = 70 \text{ m}$) for $U_{10} = 1 \text{ m/s}$ (top) and $U_{10} = 10 \text{ m/s}$ (bottom), showing
 455 the effect of wind speed on the fire dynamics in the case of non-uniform fire-ignition
 456 mode.

457

458



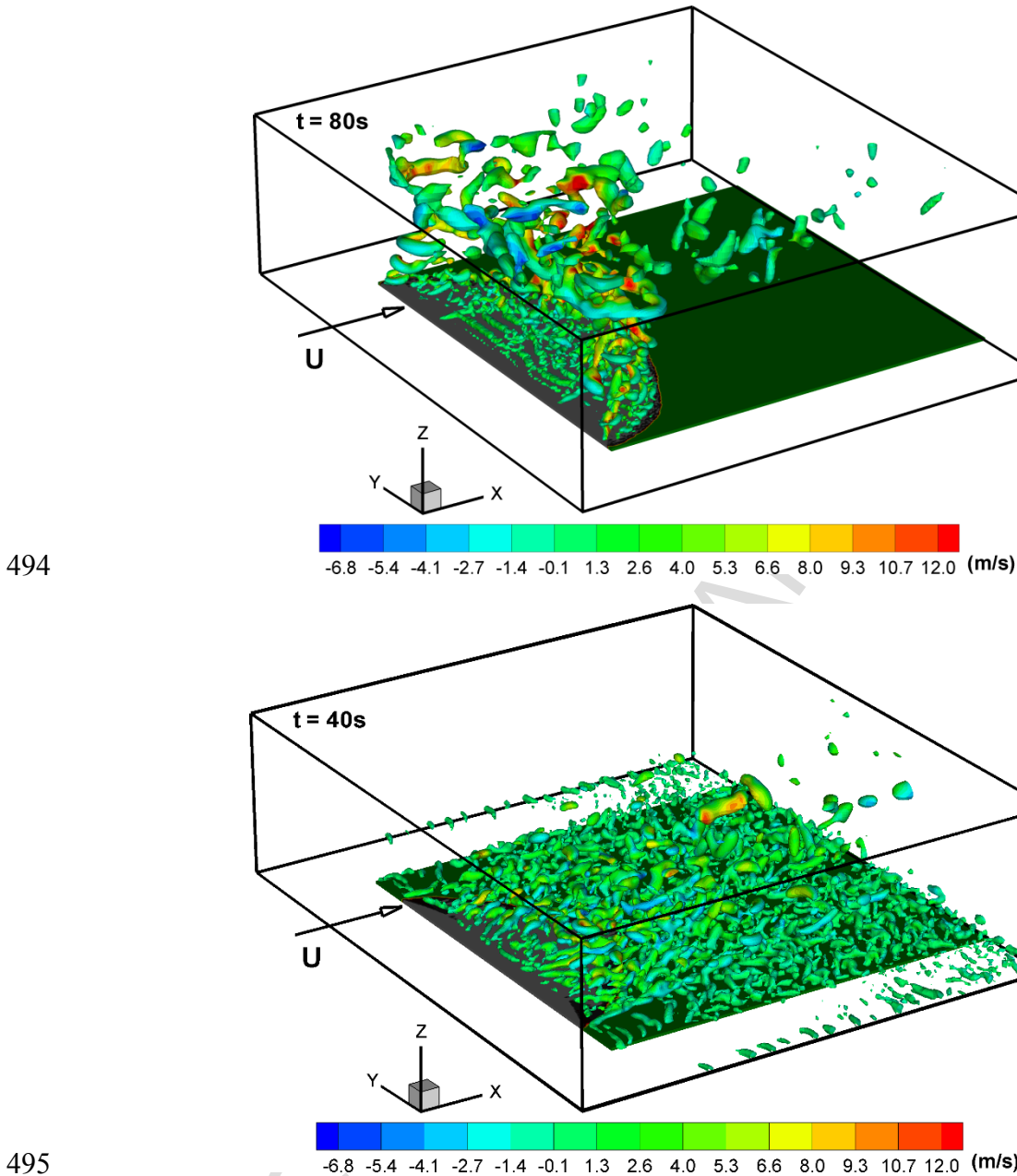
459
 460 **Figure 11.** Temperature difference between the solid fuel and the gas mixture along the
 461 line ($y = 70$ m and $z = \delta$) ahead of the fire front, obtained in the case of a non-uniform fire-
 462 ignition mode for two different 10-m open wind speeds : $U_{10} = 1$ m/s (at $t = 80$ s) and
 463 $U_{10} = 10$ m/s (at $t = 40$ s), which corresponds to the temperature fields shown in Fig. 10.
 464

465 To show the effect of wind speed on the flow structures, figure 12 shows, for two different
 466 wind speeds (1 and 10 m/s) and in the case of a non-uniform fire-ignition mode, isovalue
 467 surfaces of the Q -criterion colored by the vertical component of the velocity vector. This
 468 invariant of velocity gradient tensor represents the balance between the rotation and
 469 strain rates. The Q -criterion is an appropriate tool for the visualization of turbulent eddy
 470 formation, this criterion was introduced by Hunt et al. in 1988 [55]. The Q iso-surfaces
 471 are good indicators of coherent structures in a turbulent flow, this variable is defined as
 472 follows:

$$473 \quad Q = \frac{1}{8} \left[\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right)^2 - \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2 \right] \quad (3)$$

474 where u_i is the velocity component in direction x_i . In addition of showing the three-
 475 dimensional nature of the flow, this figure highlights the flow structures present during
 476 a grassland fire. This figure clearly shows that the assumption of a homogeneous plane
 477 made for the fire front in the radiant panel theory is not valid, the fire front is structured
 478 as a succession of peaks and troughs allowing for the air flow to find a way across it [54].
 479 This heterogeneity of the flame and the flow structure along the transverse direction,
 480 which is a great demonstration of 3D effects in a fire, affects a lot the propagation of the
 481 fire, as it has been clearly demonstrated experimentally at small scale [56] and
 482 numerically at larger scale [57]. The main effect is that, when the wind flow is able to
 483 cross the fire front, recirculating zones are formed at the back of the fire front, which
 484 redresses the flame and affects significantly the heat transfer between the flame and the
 485 vegetation and therefore the rate of spread. This effect is only visible above a certain
 486 threshold value of the wind speed. Being able to capture these flow details using an
 487 unsteady RANS approach is due to a relatively fine mesh resolution matching the
 488 extinction length scale ($4/\alpha\sigma$) characterizing the absorption of the radiation inside the

489 vegetation layer. This leads us to possibly consider a fully Large Eddy Simulation (LES)
 490 approach using a comparable mesh resolution (that seems to be sufficient to capture the
 491 flow coherent structures), where a transport equation of the turbulent kinetic energy k
 492 only needs to be solved (instead of the two-equation k - ε model).
 493



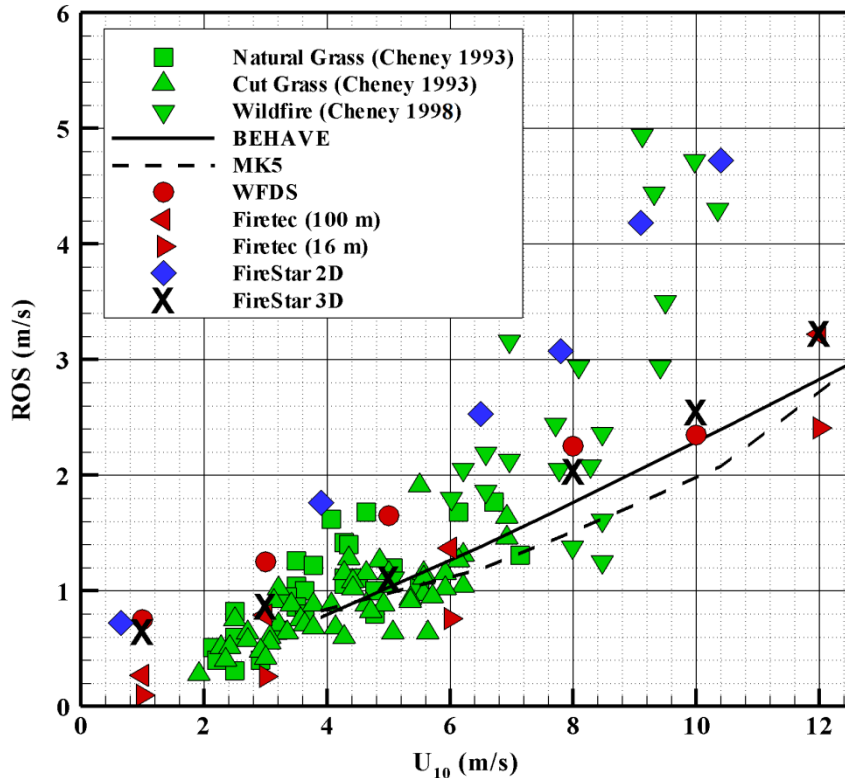
496 **Figure 12.** Flow structure in a grassland fire for two 10-m open wind speed $U_{10} = 1$ m/s
 497 (top) and $U_{10} = 10$ m/s (bottom) and for a non-uniform fire-ignition mode, shown using
 498 an isovalue surface of the Q criterion ($Q = 0.5$ s⁻²) colored by the vertical component of
 499 the velocity field.

500

501 4.2. Rate of Fire Spread

502 To go further in the analysis, we consider now two quantitative parameters,
 503 characterizing the fire: the Rate Of Spread (ROS) and the intensity of the fireline. The
 504 evolution of the ROS with the 10-m open wind speed (U_{10}) is shown by Fig. 13. The ROS

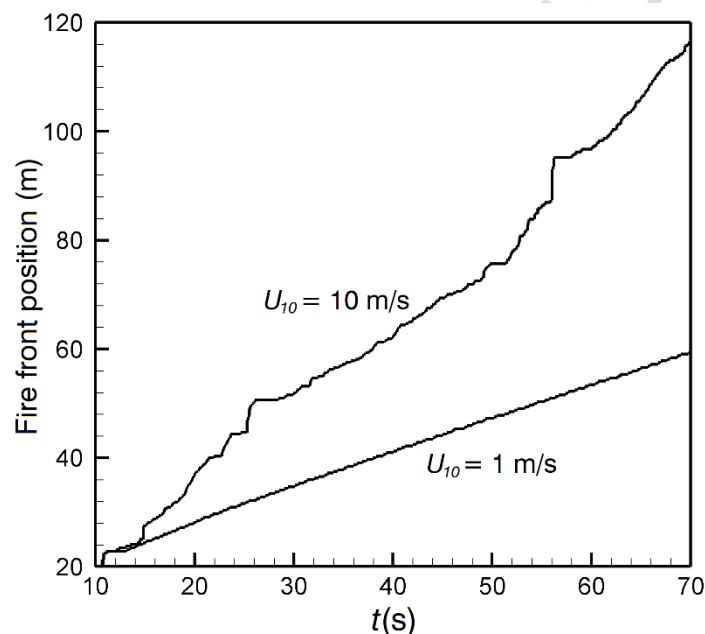
505 estimation was obtained from the time derivative of the position of the pyrolysis front at
 506 the surface of the vegetation cover. Because this operation needs a certain level of
 507 regularity of the concerned curve, it was carried out in the vertical median plane (i.e.
 508 along the line $y = 70 \text{ m}$, $z = \delta$). Since the ignition procedure was initiated from the center
 509 to the sides, the head fire was always located in the median plane. Therefore this value
 510 can be considered to the same value of the rate of spread of the head fire, where the ROS
 511 reached its maximum value.
 512



513
 514 **Figure 13.** Rate of fire spread (ROS) through a uniform grassland obtained for different
 515 10-m open wind speeds. The results of this study (FireStar3D) are compared to the
 516 results obtained experimentally (Cheney et al 1993, 1995, 1998 [27-29]), and using an
 517 empirical model (MK5 [8]), a semi-empirical model (BEHAVE [10]), 3D numerical models
 518 (FIRETEC [16], WFDS [15, 20]), and a 2D numerical model (FireStar2D [30]).
 519

520 The experimental data shown in Fig. 13 were obtained from Cheney et al. [27-29] for
 521 different lengths w of the ignition line. These experimental studies show that the ROS
 522 increases with w , as found by FIRETEC model predictions (16 m and 100 m) [16], before
 523 reaching an asymptotic value for $w > 200 \text{ m}$. For example, when w increased from 50 m
 524 to 250 m, the ROS increased by about 30% for $U_{10} = 3 \text{ m/s}$ and 6 m/s . The authors
 525 reported that this scale effect was more pronounced for larger wind speeds. Concerning
 526 the relatively large dispersion of the experimental measurements, it can result from the
 527 unsteadiness nature of the wind flow [58]. On the other hand, the reported experimental
 528 data for $U_{10} \geq 8 \text{ m/s}$ [29] were estimated from measurements recorded during real
 529 wildfires with significantly large fire front (the ROS reaches its maximum value) but for
 530 which wind speed and vegetation characteristics are not under control as in experimental
 531 fires. We recall that the simulations were carried out under conditions similar to those of
 532 experiment C064 conducted by Cheney et al. [28]. The main difference lies in the grass
 533 height ($\delta = 0.7 \text{ m}$ in the simulations compared to $\delta = 0.21 \text{ m}$ for experiment C064) and

534 this choice was mainly motivated by the existence of prior numerical studies [16,30]. For
 535 low to moderate U_{10} values (up to 6 m/s), FireStar3D results compare well with
 536 experimental data and with other predictions, and we can observe a quasi-linear
 537 evolution of the ROS. Between 1 and 5 m/s we can notice a less influence of the wind
 538 speed upon the rate of spread, this result is compatible with the transition between a
 539 plume dominated fire (for $U_{10} = 1$ m/s) and a wind driven fire ($U_{10} = 5$ m/s)[58,59]. For
 540 these values of wind speed, a steady regime of fire propagation was clearly reached in the
 541 simulations, as shown by Fig. 14 for $U_{10} = 1$ m/s from the regular and constant slope of the
 542 fire front position versus time. For $U_{10} = 8$ m/s, the results are consistent with the
 543 predictions of other models and with the experiments, despite the relative dispersion of
 544 the experimental measurements which prevents a significant comparison. For $U_{10} \geq 10$
 545 m/s, FireStar3D clearly underestimates the ROS (just as FIRETEC and WFDS do) mainly
 546 because of the short ignition-line length of 50 m that has been considered and also
 547 because of the longitudinal extension of the plot (100 m) which were too short to reach
 548 quasi-steady conditions of propagation, as shown by Fig. 14 for $U_{10} = 10$ m/s from the
 549 highly irregular evolution of the fire front position with time.
 550



551
 552 **Figure 14.** Position versus time of the furthestmost point of the pyrolysis front at the fuel-
 553 bed surface obtained in the case of a non-uniform fire-ignition mode for two different 10-
 554 m open wind speeds : $U_{10} = 1$ m/s and $U_{10} = 10$ m/s.
 555

556 To illustrate further this last point, the results obtained with WFDS reported in Fig. 13,
 557 were obtained with a plot 50 m long, with a consequence that the ROS seems to saturate
 558 above a certain value of the wind speed (8 m/s). On the other hand, FireStar2D that
 559 assumes a straight and infinite pyrolysis front better predicts the ROS at high wind speeds
 560 (10 m/s and 12 m/s). In return, 2D models fail to account for the aerodynamic drag on
 561 the lateral border of the fire front that is primarily responsible for its curvature, which
 562 results in the overestimation of the ROS at low to moderate wind speeds. Both for the
 563 empirical model (MK5) and semi-empirical one (BEHAVE), the experimental fires that
 564 helped elaborating them could not be carried out properly for wind speeds exceeding the
 565 threshold value of 7-8 m/s [10], leading to an underestimation of the ROS by these models
 566 at high wind speeds. We can explain the discrepancies between MK5, BEHAVE and field

567 measurements by the fact that for safety reasons the experiments carried out to elaborate
 568 the MK5 model cannot be conducted under strong wind conditions, whereas for BEHAVE
 569 model there is a real scaling problem in extrapolating experimental data collected at
 570 small scale in a wind-tunnel to fires at large scale such as in grassland.

571

572 4.3. Fire Intensity

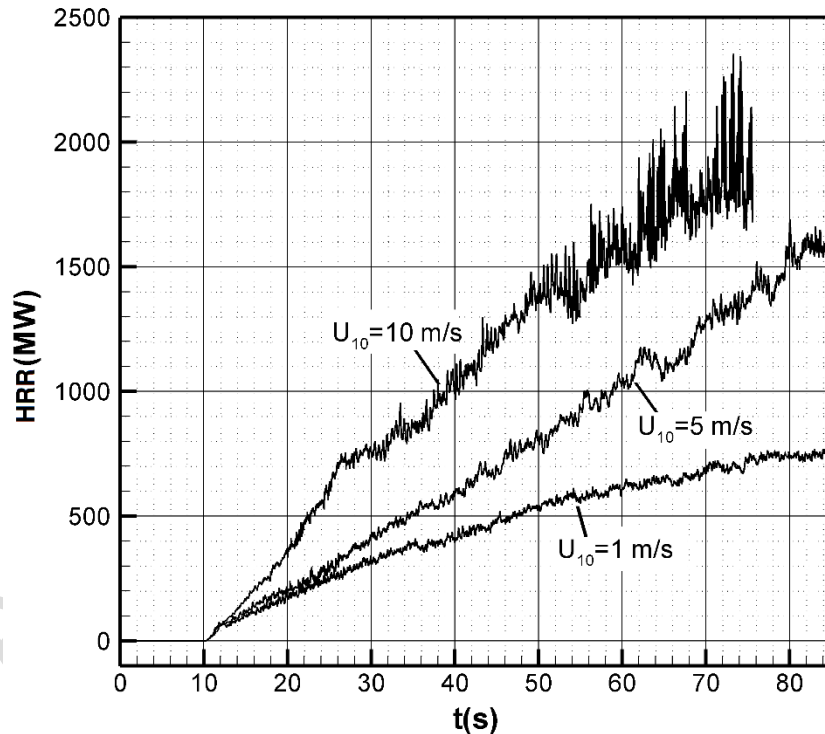
573 The fireline intensity (I_{BYR}) at the center of the fire front (maximum value) can be
 574 evaluated from Eq. 4 (Byram's intensity [60]), where $m = \alpha\rho\delta$ is the fuel load (equal to 0.7
 575 kg/m² according to Tab. 1), and ΔH is the heat yield of the fuel (estimated at about 18000
 576 kJ/kg [61]).

$$577 \quad I_{BYR} = m \times \Delta H \times ROS \quad (4)$$

578 Because this approximation is theoretically valid only for a straight front propagating at
 579 the same speed, we have chosen to evaluate numerically the fireline intensity from the
 580 Heat Release Rate (HRR) defined by Eq. 5 as the product of ΔH and the rate of total mass-
 581 loss of vegetation in the entire computational domain.

$$582 \quad I = \dot{m} \times \Delta H \quad (5)$$

583 The time evolution of the heat release rate, evaluated from Eq. 5 with $\Delta H = 18\,000$ kJ/kg,
 584 are shown in Fig. 15 (for three values of wind speed). The figure shows that the heat
 585 release rate grows until the lateral branch of the fire reach the limit of the plot, more or
 586 less at the same time (75 s) for these three values of the wind speed, mainly because the
 587 propagation of the flank fire is less affected by the air flow.



588

589 **Figure 15.** Time evolution of the Heat Release Rate (HRR) of the fire obtained from the
 590 rate of total mass-loss evaluated for the whole solid-fuel layer, in the case of non-uniform
 591 fire-ignition mode, for three different 10-m open wind speed $U_{10} = 1, 5,$ and 10 m/s. For
 592 $U_{10} = 10$ m/s, the fire front reaches the end of the domain around $t = 76$ s.

593

594 The fireline intensity can be estimated numerically by dividing the average value of the
 595 heat release rate reached when the fire was fully developed (HRR_{∞}) by the width w of the
 596 plot (100 m) according to Eq. 6.

$$597 \quad I \approx \frac{HRR_{\infty}}{w} \quad (6)$$

598 Using the fire line intensity calculated from Eq. 6, it is then possible to evaluate Byram's
 599 convective number N_C defined as the ratio between the buoyancy force and the inertial
 600 force due to the wind [59] and given by Eq. 7, where g is the acceleration of gravity (9.81
 601 m/s²), and ρ_0 (1.171 kg/m³) and C_{p0} (1010 J/kg.K) are the density and the specific heat
 602 of ambient air at temperature $T_0 = 300$ K.

$$603 \quad N_C = \frac{2gI}{\rho_0 C_{p0} T_0 (U_{10} - ROS)^3} \quad (7)$$

604 Byram's convective number is an indicator of the fire propagation regime. Large values
 605 of Byram's number are normally obtained in fires governed by plumes (plume dominated
 606 fires), with a heat transfer between the flame and the vegetation dominated by radiation.
 607 Whereas small values of Byram's number are obtained in fires piloted by inertial effects
 608 (wind driven fire), with a more important contribution of the convection heat transfer
 609 [14,59].

610 A comparison between the two methods of calculation of the fireline intensity (I_{BYR}
 611 obtained from Eq. 4 and I obtained successively from Eqs. 5 and 6) is presented in Tab. 2.
 612 We can notice that the deviation between these two approaches increases with the wind
 613 speed: for $U_{10} = 1$ m/s, the relative variation $\Delta I/I$ is equal to 26%, while for $U_{10} = 12$ m/s,
 614 $\Delta I/I$ is equal to 101%. Two factors can explain these differences: (1) in the calculation of
 615 I_{BYR} the rate of spread was evaluated at the center of the front line (where the ROS was
 616 maximum) and averaged over the propagation time of the fire; and (2) it was assumed
 617 that all the solid fuel had burned. Both these effects result in an overestimation of the
 618 quantity of fuel consumed by the fire and are therefore responsible for the
 619 overestimation of I_{BYR} (as seen in Tab. 2). Furthermore, these effects become more
 620 pronounced as the wind speed increases, which explains why the relative difference $\Delta I/I$
 621 was smaller for a wind speed of 1 m/s than for 12 m/s.

622

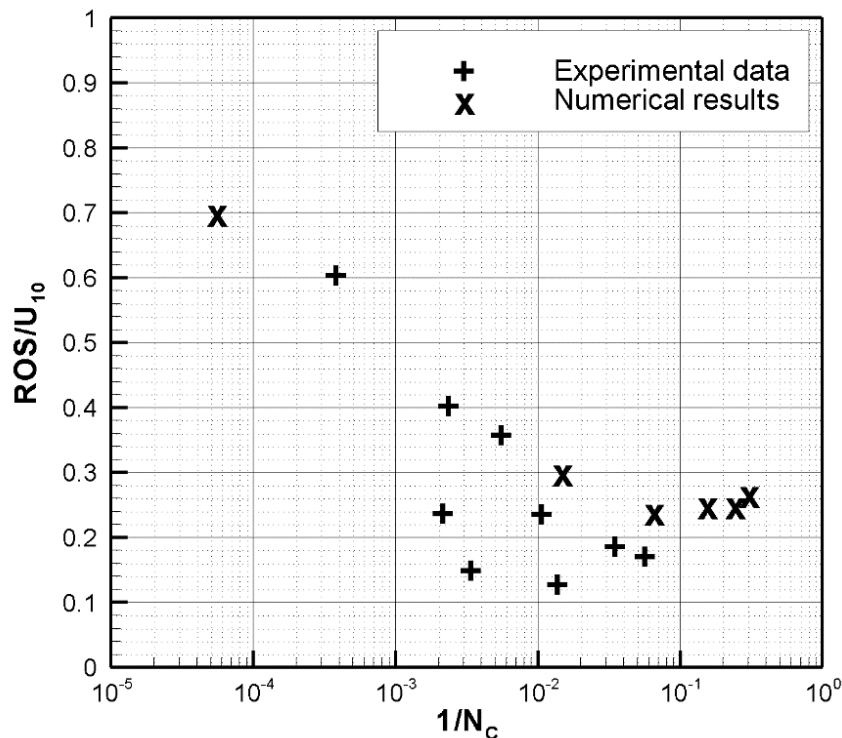
U_{10} (m/s)	1	3	5	8	10	12
I_{BYR} (kW/m)	8820	11340	15120	25200	31500	40320
I (kW/m)	7000	8000	14000	17000	19000	20000

623 **Table 2.** Fireline intensity evaluated using two approaches: (1) from the average rate of
 624 spread and assuming that the initial fuel load had fully burned (I_{BYR} , Eq. 4) and (2) from
 625 the rate of total mass-loss of solid fuel (I , Eq. 6).

626

627 To illustrate the relation between Byram's convection number and the fire regime, we
 628 notice for example that for a 10-m open wind speed $U_{10} = 1$ m/s, Byram's number N_C ,
 629 estimated from Eq. 7 using the value of the ROS from Fig. 14 and the value of I from Tab.
 630 2, is about 14300, while for $U_{10} = 10$ m/s, N_C is about 2.5. We can conclude that the
 631 situation observed for $U_{10} = 1$ m/s was clearly a plume dominated fire, and that for $U_{10} =$

632 10 m/s the situation was closer to a wind driven fire. The ratio ROS/U_{10} versus the
 633 inverse of Byram's convective number N_c (calculated from Eq. 7) is shown in Fig. 16,
 634 where the numerical results are compared to experimental data collected from the
 635 various experimental campaigns carried out in Australia [27–29, 62]. Despite some
 636 discrepancies between numerical and experimental data, the two sets of data compare
 637 relatively well. As pointed out in a previous study [17,58], the maximum value of the ratio
 638 ROS/U_{10} (equal to 0.7 in our case) is obtained for fires dominated by buoyancy (plume
 639 dominated fires), and thus for small values of the ratio $1/N_c$. On the other side of the curve
 640 (i.e. for large values of $1/N_c$), the ratio ROS/U_{10} tends towards a constant value (nearly
 641 equal to 0.25). That means that for fires dominated by inertial forces (wind driven fires)
 642 the ROS converges toward a linear relationship with the wind speed. This behavior has
 643 been reported by many experimental studies, in various ecosystems (surface fires in
 644 grassland, shrubland ...) [62]. The relatively high values observed for the two branches of
 645 the curve (comparable to the values observed on the field), can be interpreted as a
 646 consequence of the low value of the fuel moisture content ($M = 5\%$) that contributes
 647 significantly to promote the propagation of the fire, and therefore to obtain high rates of
 648 spread.
 649



650

651 **Figure 16.** Ratio ROS/U_{10} versus the inverse of Byram's convective number N_c ,
 652 comparison between numerical results and experimental data [62].

653 5. Conclusions

654 **This study reported numerical simulations of fire spread through a homogeneous**
 655 **grassland. The results were obtained using a 3D Computational Fluid Dynamic**
 656 **code based on a fully-physical multiphase model. At low to moderate wind speeds**
 657 **(up to 8 m/s), the simulated Rate Of Spread of fire (ROS) was in good agreement**
 658 **with the data of the experimental campaign conducted in Australia, with the**
 659 **predictions of operational empirical models (such as MK5 and BEHAVE), and with**

660 the numerical results of other 3D physical models (FIRETEC and WFDS). At high
661 wind speeds (10 m/s and 12 m/s), a larger extends of the vegetation cover and a
662 larger length of the ignition-line would be required in order to reach the
663 asymptotic values of the ROS. Nevertheless, the results of FireStar3D were in good
664 agreement with the predictions of other 3D physical models (FIRETEC and WFDS).
665 The study has also shown that the method of fire ignition can affect significantly
666 the shape of the fire front without affecting significantly the rate of fire spread.
667 Consequently, it seems that the non-uniform fire-ignition of the grassland
668 (consistent with the experimental procedure) allows recovering the parabolic
669 shape of the fire front observed experimentally. The analysis of the results by
670 exploiting the rate of total mass-loss of solid fuel has allowed to reconstruct the
671 evolution of the ratio ROS/U10 as a function of the inverse of Byram's convective
672 number. This parameter is a good indicator to highlight the existence of two
673 propagation regimes of surface fires, namely the plume dominated and the wind
674 driven fires. The next step of this work, would be to explore the 3D interactions
675 between a quasi-infinite width fireline (reproduced using periodic conditions at
676 the lateral boundaries of the fuel layer) and the atmospheric boundary layer.
677 Various aspects of this problem could be studied, such as the impact of the
678 unsteady nature of the wind speed, the competition between the inertial forces and
679 buoyancy, the aerology generates by the fire itself, the coherent structures
680 observed along the fire front and their impact upon the fire dynamic. These aspects
681 would be better addressed using the new simplified LES model implemented in
682 FireStar3D. This model had been validated in the case of an isothermal flow
683 through homogenous and inhomogeneous canopies [25, 26], and has been recently
684 extended to account for fire propagation. Many other fundamental aspects of the
685 wildfire dynamic are not well understood, such as the role played by the field slope
686 (and the competition between the wind and the slope when their directions are not
687 aligned), the impact of the fuel moisture content (its threshold effect in the
688 burn/no burn process, the linear or exponential decay of the rate of spread ...). In
689 complement to experimental investigations, detailed physical models (such as
690 Firestar3D) could be good tools for the understanding of the basic physical
691 processes governing the behavior of wildfires. In more practical contexts, this kind
692 of numerical simulation tools can be used to analyze the effects of the vegetation
693 layer properties (heterogeneity, discontinuity ...) or to simulate some operational
694 situations, such as prescribed burning (to evaluate the thermal impact in the soil),
695 counter-fires ignited during firefighting operations [20], or to study the efficiency
696 of a fuel break [19].

697 Acknowledgements

698 This work was granted access to the HPC resources of Aix-Marseille Université funded by
699 the project Equip@Meso (ANR-10-EQPX-29-01) of the program "Investissements
700 d'Avenir" supervised by the "Agence Nationale pour la Recherche". The authors thank the
701 anonymous reviewers for the quality of their analysis, their reports have contributed a
702 lot to improve the paper.

703

704 References

- 705 [1] R.J. Whelan, *The ecology of fire*, Cambridge studies in ecology, 1st Edition, 1995.
- 706 [2] S.J. Pyne, P.L. Andrews, R.D. Laven, *Introduction To Wildland Fire*, John Wiley &
707 Sons, New York, 2nd Edition, 1996.
- 708 [3] W.T. Sommers, S.G. Coloff, S.G. Conard, *Synthesis of Knowledge: Fire History and*
709 *Climate Change*, JFSP Synth. Reports. Pap. 19. (2011) 190.
- 710 [4] M.G. Cruz, A.L. Sullivan, J.S. Gould, N.C. Sims, A.J. Bannister, J.J. Hollis, R.J. Hurley,
711 *Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in*
712 *Victoria, Australia*, *For. Ecol. Manage.* 284 (2012) 269–285.
- 713 [5] Parliament of Victoria, 2009 Victorian Bushfires Royal Commission, in: 2009 Vic.
714 *Bushfires R. Comm.*, 2010.
- 715 [6] K.G. Tolhurst, B. Shields, D.M. Chong, *Phoenix: Development and Application of a*
716 *Bushfire Risk Management Tool*, *Aust. J. Emerg. Manag.* 23 (2008) 47.
- 717 [7] M.A. Finney, *FIRESITE: Fire Area Simulator-Model Development and Evaluation*,
718 *RMRS-RP-4*, Ogden, UT. (1998) 47.
- 719 [8] A.G. McArthur, *Weather and Grassland Fire Behaviour*, Leaflet No. 100, Canberra
720 *Aust. For. Timber Bur.* (1966) 23.
- 721 [9] A.G. McArthur, *Fire behaviour in eucalypt forests*, Leaflet No. 107, For. Res.
722 *Institute, Canberra, Aust.* (1967).
- 723 [10] R.C. Rothermel, *A mathematical model for predicting fire spread in wildland fuels*,
724 *USDA For. Serv. Res. Pap. INT USA.* (1972) 40.
- 725 [11] H.P. Hanson, M.M. Bradley, J.E. Bossert, R.R. Linn, L.W. Younker, *The potential and*
726 *promise of physics-based wildfire simulation*, *Environ. Sci. Policy.* 3 (2000) 161–
727 172.
- 728 [12] A.L. Sullivan, *Wildland surface fire spread modelling, 1990–2007. 1: Physical and*
729 *quasi-physical models*, *Int. J. Wildl. Fire.* 18 (2009) 349–368.
- 730 [13] A.M. Grishin, *Mathematical modeling of forest fires and new methods of fighting*
731 *them*, edited by F. A. Albin, Publishing House of the Tomsk University, Tomsk,
732 *Russia*, in: 1997.
- 733 [14] D. Morvan, *Physical Phenomena and Length Scales Governing the Behaviour of*
734 *Wildfires: A Case for Physical Modelling*, *Fire Technol.* 47 (2011) 437–460.
- 735 [15] W. Mell, M.A. Jenkins, J. Gould, P. Cheney, *A physics-based approach to modelling*
736 *grassland fires*, *Int. J. Wildl. Fire.* 16 (2007) 1–22.
- 737 [16] R.R. Linn, P. Cunningham, *Numerical simulations of grass fires using a coupled*
738 *atmosphere-fire model: Basic fire behavior and dependence on wind speed*, *J.*
739 *Geophys. Res.* 110 (2005) D13107.
- 740 [17] D. Morvan, S. Meradji, G. Accary, *Wildfire behavior study in a mediterranean pine*
741 *stand using a physically based model*, *Combust. Sci. Technol.* 180 (2008) 230–248.
- 742 [18] D. Morvan, J.L. Dupuy, *Modeling the propagation of a wildfire through a*
743 *Mediterranean shrub using a multiphase formulation*, *Combust. Flame.* 138 (2004)
744 199–210.
- 745 [19] D. Morvan, *Numerical study of the behaviour of a surface fire propagating through*
746 *a firebreak built in a Mediterranean shrub layer*, *Fire Saf. J.* 71 (2015) 34–48.
- 747 [20] D. Morvan, S. Meradji, W. Mell, *Interaction between head fire and backfire in*
748 *grasslands*, *Fire Saf. J.* 58 (2013) 195–203.
- 749 [21] W. Mell, S. Manzello, A. Maranghides, *The Wildland-Urban Interface Problem -*
750 *Current Approaches and Research Needs*, *Int. J. Wildl. Fire.* 19 (2010) 238.
- 751 [22] E. Koo, R.R. Linn, P.J. Pagni, C.B. Edminster, *Modelling firebrand transport in*
752 *wildfires using HIGRAD/FIRETEC*, *Int. J. Wildl. Fire.* 21 (2012) 396–417.
- 753 [23] G. Accary, S. Meradji, D. Morvan, D. Fougère, *FireStar3D-3D finite volume model for*

- 754 the prediction of wildfires behavior. *Advances in Forest Fire Research*, in: D.X.
755 Vegas Editor, (2014) 251–261.
- 756 [24] G. Accary, S. Meradji, D. Morvan, D. Fougère, Towards a numerical benchmark for
757 3D mixed-convection low Mach number flows in a rectangular channel heated from
758 below, *Fluid Dyn. Mater. Process.* 141 (2008) 1–7.
- 759 [25] K. Gavrilov, G. Accary, D. Morvan, D. Lyubimov, S. Méradji, O. Bessonov, Numerical
760 simulation of coherent structures over plant canopy, *Flow, Turbul. Combust.* 86
761 (2011) 89–111.
- 762 [26] K. Gavrilov, D. Morvan, G. Accary, D. Lyubimov, S. Meradji, Numerical simulation of
763 coherent turbulent structures and of passive scalar dispersion in a canopy sub-
764 layer, *Comput. Fluids.* 78 (2013) 54–62.
- 765 [27] N.P. Cheney, J.S. Gould, W.R. Catchpole, The influence of fuel, weather and fire
766 shape variables on fire spread in grasslands, *Int. J. Wildl. Fire.* 3 (1993) 31–44.
- 767 [28] N.P. Cheney, J.S. Gould, Fire growth in grassland fuels, *Int. J. Wildl. Fire.* 5 (1995)
768 237–247.
- 769 [29] N.P. Cheney, J.S. Gould, W.R. Catchpole, Prediction of fire spread in grasslands, *Int.*
770 *J. Wildl. Fire.* 8 (1998) 1–13.
- 771 [30] D. Morvan, S. Méradji, G. Accary, Physical modelling of fire spread in Grasslands,
772 *Fire Saf. J.* 44 (2009) 50–61.
- 773 [31] A. Favre, L.S.G. Kovaszny, R. Dumas, J. Gaviglio, M. Coantic, *La turbulence en*
774 *mecanique des fluides*. Gauthier-Villars, 1976.
- 775 [32] G. Cox, *Combustion fundamentals of fire*. Academic Press, (1995).
- 776 [33] V. Yakhot, L.M. Smith, The renormalization group, the epsilon-expansion and
777 derivation of turbulence models, *J. Sci. Comput.* 7 (1992) 35–61.
- 778 [34] S.A. Orszag, I. Staroselsky, W.S. Flannery, Y. Zhang, *Introduction to renormalization*
779 *group modeling of turbulence*. Oxford University Press, *Simul. Model. Turbul.*
780 *Flows.* (1996) 155–183.
- 781 [35] R.J. Kee, F.M. Rupley, J.A. Miller, *The Chemkin Thermodynamic Data Based*, Sandia
782 *Natl. Lab.* (1992).
- 783 [36] B.F. Magnussen, B.H. Mjertager, On mathematical modeling of turbulent
784 combustion, *Combust. Sci. Technol.* 140 (1998) 93–122.
- 785 [37] K.J. Syed, C.D. Stewart, J.B. Moss, Modelling soot formation and thermal radiation in
786 buoyant turbulent diffusion flames. In *23rd Symposium (International) on*
787 *combustion*, The Combustion Institute, Pittsburgh, 23 (1991) 1533–1541.
- 788 [38] J.B. Moss, *Turbulent Diffusion Flames*. In G. Cox (Ed.), Academic Press, London, UK,
789 1990.
- 790 [39] J. Nagle, R.F. Strickland-Constable, Oxidation of Carbon Between 1000–2000°C,
791 *Proc. Fifth Conf. Carbon.* (1962) 154–164.
- 792 [40] F.P. Incropera, D.P. DeWitt, *Fundamentals of Heat and Mass Transfer*, John Wiley
793 and Sons, 1996.
- 794 [41] R. Siegel, J.R. Howell, *Thermal Radiation Heat Transfer*. Hemisphere Publishing
795 Corporation, Washington D.C., 3rd edition, 1992.
- 796 [42] S. V. Patankar, *Numerical Heat Transfer and Fluid Flow*. Hemisphere Publishing,
797 New York, 1980.
- 798 [43] Y. Li, M. Rudman, Assessment of higher-order upwind schemes incorporating FCT
799 for convection-dominated problems, *Numer. Heat Transf. Part B Fundam.* 27
800 (1995) 1–21.
- 801 [44] H.K. and M. Versteeg W, *An introduction to Computational Fluid Dynamics, The*
802 *Finite Volume Method*. Prentice Hall, (2007).

- 803 [45] J.H. Ferziger, M. Peric, A. Leonard, Computational Methods for Fluid Dynamics.
804 Springer-Verlag, (2002).
- 805 [46] M.F. Modest, Radiative Heat Transfer Academic Press, (2003).
- 806 [47] C.R. Kaplan, S.W. Bek, E.S. Oran, Ellzey] L, Dynamics of a Strongly Radiating Insteady
807 Ethylene Jet Diffusion Flame, Combust. Flame. 96 (1994) 1–21.
- 808 [48] G. Accary, O. Bessonov, D. Foug, Optimized Parallel Approach for 3D Modelling of
809 Forest Fire Behaviour, V.E. Malyshkin (Ed.), PaCT 2007, LNCS, Springer, Heidelb.
810 4671 (2007) 96–102.
- 811 [49] G. Accary, O. Bessonov, D. Foug, Efficient Parallelization of the Preconditioned
812 Conjugate Gradient Method, V.E. Malyshkin (Ed.), PaCT 2009, LNCS, Springer,
813 Heidelb. 5968 (2009) 60–72.
- 814 [50] A. Khalifeh, G. Accary, S. Meradji, G. Scarella, D. Morvan, K. Kahine, Three-
815 dimensional numerical simulation of the interaction between natural convection
816 and radiation in a differentially heated cavity in the low Mach number
817 approximation using the discrete ordinates method, in: Proc. Fourth Int. Conf.
818 Therm. Eng. Theory Appl. Abu Dhabi, UAE, 2009.
- 819 [51] A.G. McArthur, Grassland Fire Danger Meter MkV. CSIRO Division of Forest. Annual
820 Report, 1977.
- 821 [52] R.E. Burgan, R.C. Rothermel, Behave: Fire Behavior Prediction and Fuel Modeling
822 System - FUEL Subsystem, Behave. Intermount (1984).
- 823 [53] W. Mell, J. Charney, M. Jenkins, Numerical simulations of grassland fire behavior
824 from the LANL-FIRETEC and NIST-WFDS models. George Mason University,
825 Fairfax, VA, in: EastFIRE Conf., 2005: pp. 1–10.
- 826 [54] T. Beer, The interaction of wind and fire, Boundary-Layer Meteorol. 54 (1991) 287–
827 308.
- 828 [55] J.C.R. Hunt, A.A. Wray, P. Moin, Eddies, streams, and convergence zones in turbulent
829 flows, Stud. Turbul. Using Numer. Simul. Databases, 2. Proc. 1988 Summer Progr. 1
830 (1988) 193–208.
- 831 [56] M.A. Finney, J.D. Cohen, J.M. Forthofer, S.S. McAllister, M.J. Gollner, D.J. Gorham, K.
832 Saito, N.K. Akafuah, B.A. Adam, J.D. English, Role of buoyant flame dynamics in
833 wildfire spread, in: Proc. Natl. Acad. Sci., 2015: pp. 9833–9838.
- 834 [57] R.R. Linn, J.M. Canfield, P. Cunningham, C. Edminster, J.L. Dupuy, F. Pimont, Using
835 periodic line fires to gain a new perspective on multi-dimensional aspects of
836 forward fire spread, Agric. For. Meteorol. 157 (2012) 60–76.
- 837 [58] D. Morvan, Wind effects, unsteady behaviors, and regimes of propagation of surface
838 fires in open field, Combust. Sci. Technol. 186 (2014) 869–888.
- 839 [59] R.M. Nelson, Re-analysis of wind and slope effects on flame characteristics of
840 Mediterranean shrub fires, Int. J. Wildl. Fire. 24 (2015) 1001–1007.
- 841 [60] G.M. Byram, Forest Fire Control and Use in K.P. Davis (Ed.), McGraw-Hill, New
842 York., 1959.
- 843 [61] P. Cheney, A. Sullivan, Grassfires : Fuel, Weather and Fire Behaviour, Behaviour.
844 (2008) 0–16.
- 845 [62] A.L. Sullivan, Convective Froude number and Byram's energy criterion of
846 Australian experimental grassland fires, Proc. Combust. Inst. 31 II (2007) 2557–
847 2564.
- 848

- Numerical simulations of grassland fire
- Detailed physical fire model
- Plume dominated fire, wind driven fire
- Byram's convective number

ACCEPTED MANUSCRIPT