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A 3D physical model to study the behavior of vegetation fires at laboratory scale

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Abstract

A 3D multi-physical model referred to as “FireStar3D” has been developed in order to predict the behavior of wildfires at a local scale (< 500m). In the continuity of a previous work limited to 2D configurations, this model consists of solving the conservation equations of the coupled system composed of the vegetation and the surrounding gaseous medium. In particular, the model is able to account explicitly for all the mechanisms of degradation of the vegetation (by drying, pyrolysis, and heterogeneous combustion) and the various interactions between the gas mixture (ambient air + pyrolysis and combustion products) and the vegetation cover such as drag force, heat transfer by convection and radiation, and mass transfer. Compared to previous work, some new features were introduced in the modelling of the surface combustion of charcoal, the calculation of the heat transfer coefficient between the solid fuel particles and the surrounding atmosphere, and many improvements were brought to the numerical method to enable affordable 3D simulations. The partial validation of the model was based on some comparisons with experimental data collected at small scale fires carried out in the Missoula Fire Sciences Lab’s wind tunnel, through various solid-fuel layers and in well controlled conditions. A relative good agreement was obtained for most of the simulations that were conducted. A parametric study of the dependence of the rate of spread on the wind speed and on the fuelbed characteristics is presented.

Keywords: Forest fuel fire, Detailed physical fire model, Fire physics

Nomenclature

$\bar{\phi}, \tilde{\phi}, \phi'$	Reynolds average, Favre average, and fluctuation of a generic field variable ϕ
C_D	Drag coefficient of solid particles
C_S	Heat capacity of solid particles

38	D	Diameter of cylindrical solid particles
39	F_{Di}	Drag force in direction i resulting from solid particles
40	f_v	Volume fraction of soot in the gas mixture
41	g_i	Gravity acceleration in direction i
42	h, h_α	Enthalpy of the gas mixture and enthalpy of chemical species α
43	h_s	Heat transfer coefficient between the gas mixture and the solid
44		particles
45	$\Delta h_{Char}, \Delta h_{Pyr}, \Delta h_{Vap}$	Charcoal combustion heat, pyrolysis heat, and water vaporization heat
46	I	Radiation intensity
47	J	Total irradiance
48	k	Turbulent kinetic energy
49	Nu	Nusselt number of solid particles
50	m	Superscript referring to a vegetation family
51	M	Vegetation moisture content
52	\dot{M}_α	Mass rate of production of chemical species α resulting from
53		vegetation decomposition
54	P, P_α	Pressure of the gas mixture and partial pressure of chemical species α
55		in the mixture
56	P_{th}, P_{hs}	Thermodynamic and hydrostatic pressures of the gas mixture
57	Pr, Pr_T	Laminar and turbulent Prandtl numbers of the gas mixture
58	$\dot{Q}_S, \dot{Q}_{S,Char}, \dot{Q}_{S,Conv}$	Rate of heat transferred to the solid particles (total, from solid-fuel
59		combustion, and by convection)
60	R_0, R_α	Universal ideal gas constant and specific gas constant of chemical
61		species α
62	Ra_D	Rayleigh number of cylindrical solid particles
63	Re_D	Reynolds number of cylindrical solid particles
64	Re_T	Turbulent Reynolds number
65	ROS	Rate of spread of fire
66	Sc	Schmidt number of chemical species
67	t	Time
68	T, T_s	Temperature of the gas mixture and of the solid particles
69	U	Wind speed at wind tunnel entrance
70	u_i	Velocity vector component in direction i
71	x_i	Cartesian coordinate in direction i
72	Y_α	Mass fraction of chemical specie α in the gas mixture
73	$Y_{Ash}, Y_{Char}, Y_{Dry}, Y_{H2O}$	Mass fraction of ash, charcoal, dry material, and water in solid
74		particles
75	<i>Greek symbol</i>	

76	α_G, α_S	Volume fraction of the gaseous phase and of the solid phase
77	α_{SG}	Fraction of combustion heat absorbed by solid particles
78	δ	Fuel bed depth
79	δ_{ij}	Kronecker coefficient
80	ε	Dissipation of turbulent kinetic energy
81	φ	Multiplying factor of $\nu_{O_2}^S$ depending on the molar ratio of CO to CO ₂
82		gases produced from charcoal combustion
83	λ	Thermal conductivity of the gas mixture
84	μ, μ_T, μ_e	Dynamic viscosity, turbulent viscosity, and effective viscosity of the
85		gas mixture
86	$V_{Char}, V_{Soot}, V_{CO_2}, V_{Ash}$	Mass fraction of charcoal, soot, CO ₂ gas, and ash resulting from the
87		pyrolysis of dry material
88	$\nu_{O_2}^S, \nu_{O_2}^G, \nu_{O_2}^{Soot}$	Mass stoichiometric coefficient of charcoal, CO, and soot combustion
89	$\dot{\omega}_{Char}, \dot{\omega}_{Pyr}, \dot{\omega}_{Vap}$	Rate of charcoal combustion, of dry material pyrolysis, and of water
90		vaporization in solid particles
91	$\dot{\omega}_\alpha$	Rate of production of chemical species α resulting from reaction in the
92		gaseous phase
93	$\rho, \rho_{Dry}, \rho_S, \rho_{Soot}, \rho_S^e$	Density of the gaseous phase, of dry material, of the solid phase, of
94		soot, and of solid-fuel elements
95	σ	Stephan-Boltzmann constant
96	σ_S	Surface area-to-volume ratio of the solid particles
97	σ_G	Absorption coefficient of the gas/soot mixture
98	τ_{opt}	Fuel-bed optical thickness

100 1. Introduction

101 In a near future, numerous factors such as global warming, extensive urbanization, and
 102 reduction of agriculture activities could potentially contribute to increase fire hazard in
 103 many regions worldwide [1]. However, in adopting the fire ecology point of view [2],
 104 wildfires cannot always be considered as a natural disaster, in many cases they contribute
 105 to maintain the ecological equilibrium of an ecosystem and help the renewal of forests (in
 106 eliminating old trees and promoting, after the fire, the growth of new young trees). The
 107 relationship between fires and ecosystems can be summarized by the fire regime, which
 108 integrates various characteristics of fire and is generally summarized as the observed
 109 average frequency between two fires. A modification of the fire regime, especially if it
 110 appears in a short time, is an indication of a perturbation in the life of an ecosystem due to
 111 human activities and an evolution of the climate. In this context, if a fire is ignited in a wild
 112 ecosystem, the better response could be to do nothing, considering that the perturbation
 113 induced by this fire is necessary to maintain a certain equilibrium. However, this approach

114 reaches its own limits if the fire affects urban structures such as housing developments in
115 what is commonly referred as the Wildland–Urban Interface (WUI) [3]. The reduction of
116 this natural hazard needs a better understanding of the physical mechanisms governing the
117 behavior of a fire during different phases (ignition, propagation, and extinction), the role
118 played by various parameters characterizing the structure and the state of the vegetation,
119 but also the effects of external conditions such as the wind, air temperature and humidity,
120 the topography, and many other factors. The development of new fire safety engineering
121 tools, based on numerical simulations will allow, in the near future, for the ability to predict
122 the trajectory of a fire front through a landscape (at large scale) or to describe in more
123 details the interaction at a smaller scale between the flames and potential targets located
124 inside the WUI (e.g., vegetation, houses, etc.) [4,5].

125 As highlighted in the literature, most of the operational tools developed in order to predict
126 the propagation of a fire front at a landscape scale are based on statistical or semi-
127 empirical approaches [6]. Unfortunately, the use of this class of models under conditions
128 that deviate from those used to construct the database, can lead to unacceptable failures;
129 for example, in some cases, the rate of spread of the fire can exceed the wind speed (wind
130 speed measured at a sufficient height 10m open wind speed), which is totally unphysical
131 except if the wind speed tends to zero. This has motivated the development of a new class
132 of models, based on a “fully” physical approach, for which the rate of fire spread, and more
133 generally, all variables (flame geometry, fire intensity, etc.) characterizing fire behavior are
134 addressed through the resolution of balance equations governing the various interactions
135 occurring between the vegetation, the surrounding atmosphere, and the flame [5]. The
136 multiphase approach, initially introduced by A.M. Grishin in a monograph at the end of 90’s
137 [7], is based on a very detailed modeling of the physicochemical phenomena involved in a
138 fire, from the thermal degradation of the vegetation to the development of the turbulent
139 flame inside and above the vegetation layer. The model developed in this work, referred to
140 as “FireStar3D”, can be considered to belong to this multiphase class of models. Globally,
141 this approach solves two sets of problems, one for the vegetation and one for the
142 surrounding gas. These two sets of problems are coupled through additional terms in the
143 balance equations (mass, momentum, and energy) governing the physical system. No
144 modeling of the interface between the solid phase and the gaseous one was introduced in
145 the model, the geometrical complexity (fractal in nature) does not permit an easy
146 description of this interface. In an approach similar to that used to describe fluid flow in a
147 porous medium, the equations were averaged in a representative elementary volume
148 including the two phases. This preliminary operation is responsible for the introduction of
149 additional source terms in the average balance equations (gas production due to pyrolysis,
150 drag force, convection and radiation heat exchange with the solid phase). Except for some
151 particular cases clearly indicated in the text, all the constants of the different sub-models
152 have been fixed from experimental data referenced in Grishin's monograph [7]. Of course,

153 the value of these constants are the same for all the reported simulations. Because this kind
154 of model includes a high level of details in representing a propagating fire front and its use
155 is limited to describe the behavior of a fire at a relatively local scale (few hundred meters),
156 which is compatible with the study of the interaction between a wildfire and a house or a
157 building. A very close version of this model is already operational in a 2D approximation
158 [8–10] , in this case, the problem is solved in a vertical plane defined by the direction of
159 propagation of fire. The 3D extension of the existing model enables to render the 3D effects
160 observed in real fires [11] and to represent the real heterogeneous structure of the
161 vegetation both near the surface (for the shrubs) and the canopy (trees). The main
162 difference between 2D and 3D simulations is that in 2D the fire front is assumed to form a
163 homogeneous obstacle forcing the inlet wind flow to be deviated vertically with the
164 convective plume. In 3D, the heterogeneity of the fire front, forming a succession of peaks
165 and valleys, oscillating under the action of a thermo-convective instability, allows the inlet
166 wind flow to cross the fire front. This difference of behavior of the fire front, contributes to
167 modification of the trajectory of the flame, and also of the plume, and consequently, it
168 greatly affects the interaction between the fire front and the vegetation layer. The
169 difference in behavior between 2D and 3D simulated fires have been investigated by Linn
170 et al. [11] using the coupled atmosphere-fire model HIGRAD/FIRETEC. Even in simulating a
171 quasi-infinite fire front in 3D, using cyclic conditions in the horizontal direction
172 perpendicular to the direction of propagation, the numerical results have highlighted how
173 3D effects can affect the propagation of the fire, and particularly the relationship rate of
174 spread versus wind speed.

175 The present paper has two main objectives: (i) to present some details of the 3D model and
176 (ii) to evaluate the potential of the model in predicting the rate of fire spread in well-
177 controlled experimental conditions such as the surface fire performed in the wind-tunnel of
178 the Missoula Fire Sciences Lab [12]. One of the main interests in considering the
179 experiments carried out at Missoula Laboratory was that they had been conducted with a
180 significant number of varieties of fuel particles (pines needles, excelsior, sticks) covering a
181 large range of the solid fuel parameters, such as the surface area to volume ratio, the
182 packing ratio, and the moisture content. Before tackling the problem at large scale, for
183 example, simulating grassland fire experiments carried out in Australia or in US [13,14],
184 this paper represents a first step in evaluating the numerical results obtained with our 3D
185 model to experimental laboratory-scale data collected under well-controlled conditions.

186

187 **2. Mathematical Model**

188 The mathematical model of FireStar3D consists of two main parts, coupled through
189 interaction terms. The first part is devoted to the evolution of the state of the vegetation
190 subjected to the intense heat flux coming from the flaming zone. The second part is devoted

191 to the calculation of the turbulent-reactive gas flow resulting from the mixture of the
192 pyrolysis and combustion products with the ambient air.

193 Firestar3D includes most of the characteristics already integrated in the previous 2D
194 version, i.e. a volume decomposition model to represent the different steps of degradation
195 of the vegetation (drying, pyrolysis, char oxidation), a non-equilibrium multiphase model
196 to represent all the fine fuel elements constituting a vegetation layer (foliage, twigs of
197 various diameters), a low Mach number implicit Navier-Stokes solver including a turbulent
198 combustion model in the gaseous phase, and a multiphase model to represent the radiation
199 heat transfer coming both from the gas species (H_2O , CO , CO_2 ...) and the soot [8–10].
200 Particular attention was focused on the quality of the numerical convection scheme used
201 for the resolution of the transport equations in the gaseous phase, in order to avoid
202 numerical diffusion (this is capital for turbulence modeling), as well as to the
203 parallelization of the code in order to enable affordable 3D simulations. These
204 characteristics, which can contribute to the future potential of this tool, cannot all be found
205 in the other 3D wildfire models available in the community, such as FIRETEC and WFDS
206 [15–17]. Many of these well-known tools [16,17] use an explicit solver for the resolution of
207 the Navier-Stokes equations; such solvers are usually used to simulate fully compressible
208 flows, which is not the best approach for the simulation of low Mach number flows, mainly
209 because of a wide disparity between the time scales associated with convection and the
210 propagation of acoustic waves [18]. To guarantee the stability of the numerical schemes in
211 the case of fully compressible solvers, the time step and the mesh size must verify Courant-
212 Friedrich stability criterion based on the maximum value between the speed of sound and
213 the gas flow velocity. Under the low Mach number approximation, the same criterion is
214 only based on the gas flow velocity. For low Mach number flows, this constitutes a great
215 difference (if one is not interested in the propagation of acoustic waves) since the time step
216 can be easily multiplied by a factor ranged between 10 and 100 (depending the robustness
217 of the convection scheme) without any loss of accuracy in the description of the
218 phenomena of interest. In summary, choosing a fully compressible formulation and an
219 associated explicit solver, as in FIRETEC for example, constitutes a major limitation
220 especially to simulate wildfire at large scale. This is the main reason behind the mesh size
221 used in FIRETEC that can reach, for example, one meter high at ground level, exceeding
222 sometimes the height of the fuel layer, with the consequence that the pyrolysis process and
223 the heat release due to the combustion within the entire fuel layer thickness take place
224 inside one and the same computational cell. In addition, other physical aspects (turbulent
225 combustion, radiation heat transfer, soot production and transport ...) are not well
226 described in WFDS and FIRETEC, especially within the fuel layer. An overview of the
227 discrepancies between these different “fully” physical fire-models can be found in reference
228 [15], summarized also in Tab. 1.

229 As indicated in the introduction, some new features have been added in FireStar3D, such as
 230 the process of charcoal combustion and the evaluation of the heat transfer coefficient
 231 between the solid phase and the gaseous one. These new features are presented in the
 232 following parts.
 233
 234
 235

	FireStar2D	FireStar3D	WFDS	FIRETECH	FIREFOAM
Solver	2D-Implicit	3D-Implicit	3D-Explicit	3D-Explicit	3D-Implicit
Low Mach model	Yes	Yes	Yes	No	Yes ⁽¹⁾
Turbulence	TRANS	TRANS/LES	LES	LES	LES
TRI model	Yes	No	Yes ⁽²⁾	Yes ⁽²⁾	No
Combustion model	Yes	Yes	Yes	No ⁽³⁾	Yes
Multi-fuel model	Yes	Yes	Yes	Yes	No
Small scale	Yes	Yes	Yes	No	Yes
Large scale	Yes ⁽⁴⁾	Yes	Yes	Yes	Yes

236

Tab. 1. Summary of main characteristics of four fully physical fire models. ⁽¹⁾ Work in progress. ⁽²⁾ The radiation heat transfer was increased empirically. ⁽³⁾ Pyrolysis and combustion take place at the same location without transport into the gaseous phase. ⁽⁴⁾ With the limitation introduced by the 2D assumption.

237

238 2.1. Solid-Fuel Model

239 The heterogeneous character of the vegetation accounted for using two possible shape-
 240 families of solid fuel particles: cylindrical particles (used to represent branches, twigs, and
 241 needles), and disks (used to represent flat leaves). At all steps of the decomposition
 242 process, each solid fuel family m is characterized using a set of physical variables: the
 243 volume fraction (α_s), the dry material density (ρ_{dry}), the moisture content (M), the surface
 244 area-to-volume ratio (σ_s), the temperature (T_s), and the evolution of the composition of
 245 fuel particles in terms of mass fraction of char, water and dry fuel. Measurements of the fire
 246 residence time measured for homogeneous solid-fuel beds in laboratory [19], have shown
 247 that only small fuel particles ($\sigma_s > 600 \text{ m}^{-1}$ corresponding to a diameter $D < 6 \text{ mm}$ for
 248 cylindrical shape particles) can contribute actively to the dynamics of a fire. This result was
 249 confirmed by wildfire observations, showing that about 90% of thin fuel particles ($D < 6$
 250 mm) were consumed in the flaming zone [20]. This threshold represents also the limit
 251 separating the thermally thick and thermally thin particles, which means that the
 252 temperature gradient inside each solid fuel particles can be neglected in a first
 253 approximation. Thermal analysis of forest fuel samples has highlighted that this kind of
 254 material were composed of a mixing of lignin, cellulose, hemicellulose, and extractives [21].

255 The composition between these various chemical compounds varies from one species to
 256 another and between different parts of a plant (bark, branch, twigs, and foliage). At
 257 relatively small heating rate (such as the conditions used in thermogravimetric analysis),
 258 the chemical composition of fuel particles can affect the dynamics of thermal
 259 decomposition, but at higher heating rate (such as the intense heat flux coming from the
 260 flaming zone) the result are less sensitive to chemical composition [21] and seems to be
 261 more affected by other parameters such as the surface area-to-volume ratio and the fuel
 262 moisture content [22, 24]. For these reasons, we consider: (i) that the decomposition of
 263 each vegetation family (regardless its composition) can be summarized in three main steps:
 264 dehydration, pyrolysis (in only one step), and surface oxidation, (ii) that each family
 265 consists locally of a mixture of water, dry material (cellulose, hemicellulose, and lignin),
 266 char, and ash (mineral residue). These components are represented by their mass
 267 fractions: Y_{H2O} , Y_{Dry} , Y_{Char} , and Y_{Ash} respectively, resulting in a local density ρ_S of the solid-
 268 fuel.

269 The solid-fuel model consists of decomposing the fuelbed zone into homogeneous solid-
 270 fuel element of effective density $\rho_S^e = \alpha_S \rho_S$. It is assumed that the pyrolysis process would
 271 be activated only if the dehydration was entirely completed, and that surface oxidation
 272 would begin only if the pyrolysis process came to an end.

273 In the dehydration phase, the evapotranspiration process is reduced to a simple
 274 vaporization, during which the temperature of the solid fuel element T_S is assumed to
 275 remain constant at 373K. The rate of heat transfer \dot{Q}_S received by that fuel element from
 276 the flaming zone only serves to produce water vapor at the mass rate:

$$\dot{w}_{vap} = \dot{M}_{H2O} = \dot{Q}_S / \Delta h_{vap} \quad (1)$$

279 where $\Delta h_{vap} = 2.25 \times 10^3$ kJ/kg is the heat of vaporization.

281 The decomposition of dry combustible by pyrolysis produces gaseous products (CO and
 282 CO₂) and charcoal. The decomposition of 1 kg of dry combustible is assumed to produce
 283 $v_{Char} = 0.338$ kg of carbon (0.288 kg of charcoal and 0.05 kg of soot), $v_{CO2} = 0.2$ kg of CO₂ and
 284 $1 - v_{Char} - v_{CO2} = 0.462$ kg of CO. By contact with the oxygen contained in the ambient air, the
 285 hot combustible pyrolysis-products (CO and soot) ignite homogeneously in the gaseous
 286 phase. Taking into account these assumptions, the pyrolysis process obeys to the following
 287 transformation equation written for 1kg of dry combustible:



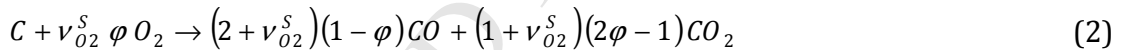
288 The pyrolysis process is assumed to take place when the solid fuel element T_S is between
 289 400K and 500K [8, 19, 21] at the mass rate:

290

$$\dot{\omega}_{pyr} = \frac{\dot{Q}_S}{\Delta h_{pyr}} \times \frac{T_S - 400}{500 - 400} \quad (3)$$

291 where Δh_{pyr} is the pyrolysis heat that depend on the vegetation species. We can notice that
 292 this range of temperature values is slightly lower than the range 473-573 K found in [21].
 293 This discrepancy can be explained by a scale effect: in the present study, the solid-fuel
 294 temperature represents an average value evaluated within a 1 cm³ volume (with a
 295 temperature gradient reported in [21]), whereas the temperature reported in [21] was
 296 measured with a 0.5 mm thermocouple. In addition, this temperature range [400-500 K]
 297 has allowed us to obtain the best results in comparison with experimental data obtained at
 298 the same scale and comparable solid fuel [25] (see also Fig. 1 in reference [8]). Thus
 299 according to Eq. 3, a portion of the rate of heat transfer \dot{Q}_S received by the fuel element
 300 contributes to the pyrolysis process, while the remaining portion of \dot{Q}_S continues to
 301 increase the solid fuel temperature T_S . Note that T_S cannot exceed 500K as long as the
 302 pyrolysis process has not ended.
 303

304 Unlike previous works [8–10] that arbitrary assumed a complete combustion of charcoal
 305 (thus producing only CO₂) at the solid-fuel particles, in the present work the model
 306 representing the surface oxidation of charcoal has been modified to account for a possible
 307 incomplete combustion, thus producing both CO and CO₂. According to [23], the balance
 308 equation written for 1kg of charcoal is given by:



309 where $\nu_{O_2}^S = 8/3$ and $\nu_{O_2}^S \varphi$ is the mass stoichiometric coefficient, it depends on the molar
 310 ratio of CO to CO₂ gases produced from charcoal combustion and is given by:

$$\varphi = \frac{2 + CO/CO_2}{2 \times CO/CO_2 + 2} \quad (3)$$

311 The molar ratio of CO to CO₂ gases depends on the surface temperature T_S according to the
 312 following relation [23]:

$$CO/CO_2 = 2500 \exp(-6240/T_S) \quad (4)$$

313 At low temperatures, $\varphi \rightarrow 1$ and only CO₂ is produced, while at high temperatures, $\varphi \rightarrow 0.5$
 314 and only CO is practically produced.

315 The reaction rate of charcoal combustion is approximated by the following Arrhenius law:

$$\dot{\omega}_{char} = k_{char} P_{O_2} \exp(-E_{char}/R_0 T_S) \alpha_S \sigma_S \quad (7)$$

316
 317 where P_{O_2} is the partial pressure of O₂ at the solid fuel particle surface. The frequency
 318 factors $k_{char} = 254.2$ kg/(m².s.atm) and activation energy $E_{char}/R_0 = 9000$ K are evaluated
 319 experimentally from a thermal analysis [23].
 320
 321

322 Heat released during charcoal combustion, taking place at the surface of a solid-fuel
 323 particle, is assumed to be absorbed both by the solid-fuel element and by the gaseous
 324 phase. The rate of heat absorbed by the solid-fuel element is calculated as follows:

$$325 \dot{Q}_{S,Char} = \alpha_{SG} \Delta h_{Char} \dot{\omega}_{Char} \quad (8)$$

327 where Δh_{Char} is the combustion heat given by:

$$328 \Delta h_{Char} = (2 + \nu_{O_2}^s)(1 - \varphi) \Delta h_{CO} + (1 + \nu_{O_2}^s)(2\varphi - 1) \Delta h_{CO_2} \quad (5)$$

329 with $\Delta h_{CO} = 9$ MJ/kg and $\Delta h_{CO_2} = 30$ MJ/kg are the reaction heats of incomplete and
 330 complete combustion of carbon that can be obtained from Eq. (2) by setting φ at 0.5 and 1
 331 respectively. We assume in this study that heat released during charcoal combustion is
 332 equally shared by the gaseous phase and by the solid-fuel element, i.e. $\alpha_{SG} = 0.5$.

333 Taking into account all the previous equations and assumptions, time evolution of the
 334 composition and the temperature of a family m of solid-fuel particles in the fuelbed are
 335 controlled by the following set of six equations [8–10]:

$$336 \frac{d}{dt} (\alpha_S^m \rho_S^m Y_{H_2O}^m) = -\dot{\omega}_{vap} \quad (10)$$

$$337 \frac{d}{dt} (\alpha_S^m \rho_S^m Y_{Dry}^m) = -\dot{\omega}_{pyr} \quad (11)$$

$$338 \frac{d}{dt} (\alpha_S^m \rho_S^m Y_{Char}^m) = (\nu_{Char} - \nu_{Soot}) \dot{\omega}_{pyr} - \left(1 + \frac{\nu_{Ash}}{\nu_{Char}}\right) \dot{\omega}_{Char} \quad (12)$$

$$339 \frac{d}{dt} (\alpha_S^m \rho_S^m) = -\dot{\omega}_{vap} - (1 - \nu_{Char} + \nu_{Soot}) \dot{\omega}_{pyr} - \dot{\omega}_{Char} \quad (13)$$

$$340 \frac{d}{dt} (\alpha_S^m) = -\frac{1}{\rho_S^m} \dot{\omega}_{Char} \quad (14)$$

$$341 \alpha_S^m \rho_S^m C_S^m \frac{dT_S^m}{dt} = \dot{Q}_S^m - \dot{\omega}_{vap} \Delta h_{vap} - \dot{\omega}_{pyr} \Delta h_{pyr} + \alpha_{SG} \Delta h_{Char} \dot{\omega}_{Char} \quad (15)$$

344 The heat capacity C_s^m characterizing locally each solid-fuel element is obtained from a mass
 345 fraction-weighted linear combination of the heat capacities of water, dry material, charcoal,
 346 and ash. $v_{Ash} = 0.033$ is the mass fraction of ash in the solid fuel.

347 The rate of heat transfer \dot{Q}_S received by a solid-fuel element results from convection and
 348 radiation heat exchanges with the hot gases and is given by [8–10]:

$$\dot{Q}_S = h_S \alpha_S \sigma_S (T - T_S) + \alpha_S \sigma_S (J - 4 \sigma T_S^4)/4 \quad (16)$$

350 where T is the temperature of the gas mixture at the surface of the solid fuel element, $\sigma =$
 351 $5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ is the Stephan-Boltzmann constant, and J is the total irradiance (fuel
 352 particles are assumed to behave as a black body). The convection heat transfer coefficient
 353 h_S depends on the shape of the fuel particles and their characteristic length. For example,
 354 for a vegetation family with cylindrical shape particles, h_S is obtained from:

$$Nu = \frac{h_S D}{\lambda} \quad (6)$$

356 where Nu is Nusselt number based of the diameter D of a cylindrical solid-particle, and λ is
 357 the thermal conductivity of the gas mixture. Unlike previous works [8–10] that only
 358 accounted for forced convection, the Nusselt number in the present study accounts for both
 359 forced and natural convection and is given by:

$$Nu = (Nu_{FC}^2 + Nu_{NC}^2)^{1/2} \quad (7)$$

360 where Nu_{FC} and Nu_{NC} are respectively the forced convection and natural convection Nusselt
 361 numbers. Nu_{FC} and Nu_{NC} are correlated to Prandtl number Pr of the gas mixture and to the
 362 Reynolds number Re_D and to the Rayleigh number Ra_D based on the diameter D of a
 363 cylindrical solid-particle as follows [26]:

$$Nu_{FC} = \begin{cases} (0.43 + 0.5 Re_D^{0.5}) Pr^{0.38} & \text{if } Re_D < 1300 \\ 0.25 Re_D^{0.6} Pr^{0.38} & \text{if } Re_D > 1300 \end{cases} \quad (8)$$

$$Nu_{NC}^{1/2} = 0.6 + \frac{0.387 Ra_D^{1/6}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{9/16}\right)^{8/27}} \quad (9)$$

364 Similar expressions are used to evaluate the convection heat transfer coefficient h_S for flat
 365 solid-fuel particles.

366 2.2. Gas-Phase Model

367 The evolution of the state of the gaseous phase (composition, velocity, temperature ...)
 368 resulting from the thermal degradation of the vegetation and the combustion reactions is
 369 governed by the balance equations of mass, momentum, and energy. Since the flow regime

370 is unsteady and fully turbulent in various regions of the computation domain, the equations
 371 are filtered using a mass-weighted average TRANS (Favre) formulation [27]. Hence, the
 372 filtered variables are governed by the following set of transport equations solved in the low
 373 Mach number approximation [18, 28]:

374

375

$$\frac{D\bar{\rho}}{Dt} = \sum_m \sum_{\alpha} \dot{M}_{\alpha}^m \quad (21)$$

376

377

$$\frac{D(\bar{\rho}\tilde{u}_i)}{Dt} = -\frac{\partial\bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\bar{\mu} \left(\frac{\partial\tilde{u}_i}{\partial x_j} + \frac{\partial\tilde{u}_j}{\partial x_i} - \frac{2}{3} \frac{\partial\tilde{u}_l}{\partial x_l} \delta_{ij} \right) \right] - \frac{\partial}{\partial x_j} (\overline{\rho u'_i u'_j}) + (\rho - \rho_0) g_i - \sum_m F_{Di}^m \quad (22)$$

378

379

$$\frac{D(\bar{\rho}\tilde{h})}{Dt} = -\frac{\partial\bar{P}_{th}}{\partial t} + \frac{\partial}{\partial x_j} \left[\frac{\bar{\mu}}{Pr} \frac{\partial\tilde{T}}{\partial x_j} \right] - \frac{\partial}{\partial x_j} (\overline{\rho u'_i h'}) + (1 - \alpha_{SG}) \Delta h_{char} \sum_m \dot{\omega}_{char}$$

380

$$+ \sum_m \sum_{\alpha} \dot{M}_{\alpha}^m \tilde{h}_{\alpha} + \sum_m \dot{Q}_{S,conv}^m + \alpha_G \sigma_G (J - 4\sigma\tilde{T}^4)$$

381

382

(23)

$$\frac{D(\bar{\rho}\tilde{Y}_{\alpha})}{Dt} = \frac{\partial}{\partial x_j} \left[\frac{\bar{\mu}}{Sc} \frac{\partial\tilde{Y}_{\alpha}}{\partial x_j} \right] - \frac{\partial}{\partial x_j} (\overline{\rho u'_i Y_{\alpha}'}) + \bar{\omega}_{\alpha} + \sum_m \dot{M}_{\alpha}^m$$

383

(24)

384 In these equations, all transported variables ϕ (density ρ , velocity components u_i , enthalpy
 385 h , and mass fractions Y_{α} of chemical species α : CO, O₂, CO₂, H₂O, and N₂) are decomposed as
 386 a sum of two contributions (Reynolds average + fluctuation: $\phi = \bar{\phi} + \phi'$). On the other
 387 hand, Favre average is defined by: $\tilde{\phi} = \overline{\rho\phi}/\bar{\rho}$. The differential operator D/Dt is defined as:

$$\frac{D\phi}{Dt} = \frac{\partial\phi}{\partial t} + \frac{\partial(\tilde{u}_j\phi)}{\partial x_j} \quad (10)$$

388 The effective gas-phase density is defined as $\rho = \alpha_G \rho_G$, where ρ_G is the density of the gas-
 389 mixture and α_G is the volume fraction of the gaseous given by:

$$\alpha_G = 1 - \sum_m \alpha_s^m \quad (11)$$

390 where α_s^m is the volume fraction of family m of solid-fuel particles. ρ_0 is the initial gas-phase
 391 density that is stratified due to gravity, g_i being gravity component in x_i direction.

392 In the low Mach number approximation [18, 28], the acoustic filtering results in splitting
 393 the pressure of the gas-mixture, into three contributions: the dynamic pressure P acting to
 394 balance inertial and external forces, the thermodynamic pressure P_{th} that is spatially
 395 homogeneous, and the hydrostatic pressure P_{hs} that is time-independent and balances the
 396 initial density stratification.

397 In addition to the previous equations, the gas mixture is assumed to behave like an ideal
 398 gas. Hence, in low Mach number approximation, the gas-phase density is obtained from the
 399 following equation of state:

$$\bar{P}_{th} + \bar{P}_{hs} = \bar{\rho} \left(\sum_{\alpha} R_{\alpha} \tilde{Y}_{\alpha} \right) \tilde{T} \quad (12)$$

400 where R_{α} (J/kg.K) is the ideal gas constant of chemical species α (universal gas constant
 401 divided by the molar mass).

402 The gaseous phase is assumed also to behave as a Newtonian fluid with a viscosity $\mu = \alpha_G \mu_G$,
 403 where μ_G is the dynamic viscosity of the gas mixture obtained from those of the chemical
 404 species (μ_{α}) using a mass fraction-weighted linear combination. The dependence of μ_{α} on
 405 temperature is governed by Sutherland law:

$$\bar{\mu}_{\alpha} = \mu_{\alpha}^{ref} \left(\frac{\tilde{T}}{T_{ref}} \right)^{1.5} \left(\frac{T_{ref} + S}{\tilde{T} + S} \right) \quad (13)$$

406 where $T_{ref} = 273\text{K}$, $S = 110.4\text{K}$, and μ_{α}^{ref} is the dynamic viscosities of the chemical species α
 407 at temperature T_{ref} . As for dry air in standard conditions, Prandtl and Schmidt numbers are
 408 both set to 0.71.

409 The term F_{Di}^m denotes the i^{th} component of the drag force resulting from the dynamic
 410 interaction between the gas flow and the vegetation family m , it is given by:

$$F_{Di} = \bar{\rho} |\tilde{u}_i| \tilde{C}_D a_L \quad (14)$$

411 where $a_L = \alpha_S \sigma_S / 2$ is the leaves area density and C_D is the drag coefficient obtained from
 412 correlations that depend on the particles shape of the vegetation family m and on the
 413 Reynolds number based on the characteristic length of solid particles [26]. For example, for
 414 a vegetation family with cylindrical particles (twigs, needles), the evolution of the drag
 415 coefficient with Reynolds number based on the diameter D of the particle is given by:

$$C_D = 1.17 + \frac{5.93}{Re_D^{0.5}} \quad (15)$$

416 Similar expressions are used to evaluate the drag coefficient C_D for flat solid-fuel particles
 417 such as leaves.

418 The enthalpy h of the gas mixture is obtained from a mass fraction-weighted linear
 419 combination of the enthalpies h_{α} of the chemical species (CO, O₂, CO₂, H₂O, and N₂). For
 420 each chemical species, the enthalpy-temperature dependence is obtained from CHEMKIN
 421 thermodynamic data base [29]:

$$\tilde{h}_{\alpha} = \beta_{\alpha,0} + \sum_{n=1}^5 \frac{1}{n} \beta_{\alpha,n} \tilde{T}^n \quad (16)$$

422 The term $\dot{Q}_{S,Conv}^m$ is the average rate of heat exchange by convection between the gas
 423 mixture and the solid-fuel family m , obtained from Eq. **Error! Reference source not**
 424 **found..** σ_g is the radiation absorption coefficient of the gas-soot mixture (including the
 425 absorption due to the presence of CO, CO₂, H₂O, and soot particles in the flame and the
 426 plumes [30]).

427 During the thermal decomposition of each solid-fuel family m , O₂ gas is consumed, CO, CO₂,
 428 and H₂O gases, and charcoal soot particles are produced at the following mass flow rates:

$$430 \dot{M}_{O_2} = -v_{O_2}^S \dot{\omega}_{Char} \quad (32)$$

$$432 \dot{M}_{CO} = (1 - v_{Char} - v_{CO_2}) \dot{\omega}_{Pyr} + (2 + v_{O_2}^S) (1 - \varphi) \dot{\omega}_{Char} \quad (33)$$

$$433 \dot{M}_{CO_2} = v_{CO_2} \dot{\omega}_{Pyr} + (1 + v_{O_2}^S) (2\varphi - 1) \dot{\omega}_{Char} \quad (34)$$

$$434 \dot{M}_{H_2O} = \dot{\omega}_{vap} \quad (35)$$

$$435 \dot{M}_{Soot} = v_{Soot} \dot{\omega}_{Pyr} \quad (36)$$

436 These rates contribute to the source terms of the balance equations of mass, energy and
 437 chemical species. Finally, $\bar{\omega}_\alpha$ is the rate of production or destruction of the chemical species
 438 α resulting from combustion in the gaseous phase, this part is detailed in the combustion
 439 modeling section.

441 2.3. Turbulence Modeling

442 The double correlations representing the action of the fluctuations on the average
 443 transport equations are evaluated using the eddy viscosity concept [31] and generalized
 444 gradient diffusion of the scalar quantities ϕ as follows:

$$-\overline{\rho u'_i u'_j} = \mu_T \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) - \frac{2}{3} \left(\mu_T \frac{\partial \tilde{u}_l}{\partial x_l} + \bar{\rho} k \right) \delta_{ij} \quad (17)$$

$$-\overline{\rho u'_i \phi'} = \frac{\mu_T}{Pr_\phi} \frac{\partial \tilde{\phi}}{\partial x_i} \quad (18)$$

445 The turbulent viscosity μ_T is evaluated from the turbulent kinetic energy k and its
 446 dissipation rate ε , and an adapted version of RNG- k - ε turbulence model in a high Reynolds
 447 number formulation is used [32].

$$\mu_T = f_\mu \bar{\rho} C_\mu k^2 / \varepsilon \quad (19)$$

448 where $C_\mu = 0.085$ and f_μ is a damping function given by Eq. (40) that accounts for low-
 449 Reynolds-number effects and allows for a better handling of laminar flow regions.

$$\ln(f_\mu) = -3.4(1 + Re_T/50)^{-2} \quad (20)$$

450 $Re_T = \bar{\rho}k^2/\mu\varepsilon$ is the turbulent Reynolds number. In the limit of a high Reynolds number
 451 ($\mu/\mu_T \ll 1$), Equations (19) and (20) result in: $\mu_T = \bar{\rho}C_\mu k^2/\varepsilon$.

452 The fields of the turbulent kinetic energy k and its dissipation rate ε are calculated from the
 453 two following transport equations:

$$\frac{D(\bar{\rho}k)}{Dt} = \frac{\partial}{\partial x_j} \left(\frac{\mu_e}{Pr_T} \left(\frac{\partial k}{\partial x_j} \right) \right) + P_k + W_k - \bar{\rho}\varepsilon + \frac{1}{2} \bar{\rho} |\tilde{u}| \sum_m C_D^m \alpha_S^m \sigma_S^m (C_{Pw} |\tilde{u}|^2 - C_{\varepsilon w} k) \quad (21)$$

$$\begin{aligned} \frac{D(\bar{\rho}\varepsilon)}{Dt} = & \frac{\partial}{\partial x_j} \left(\frac{\mu_e}{Pr_T} \left(\frac{\partial \varepsilon}{\partial x_j} \right) \right) + C_{1\varepsilon} \left(\frac{P_k}{\tau} + C_{3\varepsilon} \frac{W_k}{\tau} \right) + (C_{2\varepsilon} + R) \bar{\rho} \frac{\varepsilon}{\tau} \\ & + \frac{1}{2} \bar{\rho} |\tilde{u}| \sum_m C_D^m \alpha_S^m \sigma_S^m \left(C_{P\varepsilon w} |\tilde{u}|^2 \frac{\varepsilon}{k} - C_{D\varepsilon w} \varepsilon \right) \end{aligned} \quad (22)$$

454 The effective viscosity $\mu_e = \mu_T + \bar{\mu}$, P_k and W_k are respectively the terms contributing to the
 455 production of turbulence, due to shear and buoyancy effects [31], given by:

$$P_k = -\overline{\rho u'_i u'_j} \frac{\partial \tilde{u}_i}{\partial x_j} \quad \text{and} \quad W_k = -\frac{\mu_T}{\bar{\rho} Pr_T} \frac{\partial \bar{\rho}}{\partial x_j} g_j \quad (23)$$

456 The effective Prandtl number is computed by iteration using Eq. (24) derived analytically in
 457 the RNG theory, where $Pr_0 = 1$ for $Pr = Pr_T$, and $Pr_0 = Pr = Sc$ for $Pr = Pr_\phi$

$$\left| \frac{Pr^{-1} - 1.3929}{Pr_0^{-1} - 1.3929} \right|^{0.6321} \left| \frac{Pr^{-1} + 2.3929}{Pr_0^{-1} + 2.3929} \right|^{0.3679} = \frac{\bar{\mu}}{\mu_e} \quad (24)$$

458 In Eq. (41) and (42), the terms proportional to the drag coefficient C_D^m represent the
 459 production and destruction of turbulence resulting from the interaction between the
 460 boundary layer flow and the vegetation layer [33].

461 In the transport equation of ε , τ is the maximum between the integral turbulence time scale
 462 (k/ε) and $6\tau_\eta$, where $\tau_\eta = (\bar{\mu}/\bar{\rho}\varepsilon)^{1/2}$ is the Kolmogorov time scale. This treatment ensures
 463 that the time scale associated to the more powerful turbulent structures cannot be smaller
 464 than 6 times the turbulence dissipation scales.

465 The additional source term R in the transport equation of ε results from the RNG theory
 466 [32] and has extended the validity of this model to weak turbulent flow regions, i.e. near a
 467 wall or in the wake region, where turbulence is far from isotropic or homogeneous.

$$R = C_\mu \eta^3 (1 - \eta/\eta_0) / (1 + \beta \eta^3) \quad (25)$$

468 where $\eta = (P_k/C_\mu \bar{\rho} \varepsilon)^{1/2}$, $\eta_0 = 4.38$ and $\beta = 0.012$.

469 The following set of constants is introduced in the turbulence model [31]: $C_{1\varepsilon} = 1.42$ and
 470 $C_{2\varepsilon} = 1.68$. On the other hand, the degree to which ε is affected by buoyancy is determined
 471 by the constant $C_{3\varepsilon}$ calculated according to the following relation:

$$C_{3\varepsilon} = \tanh \frac{|\tilde{u}_j g_j|}{\left(\tilde{u}_j \tilde{u}_j |g|^2 - (\tilde{u}_j g_j)^2 \right)^{0.5}} \quad (26)$$

472 The terms including the drag coefficient in $k-\varepsilon$ equations represent the action of the drag
 473 force resulting from the vegetation on the turbulent kinetic energy balance. The following
 474 set of constants is used in these terms [33]: $C_{P\varepsilon} = 0.8$, $C_{\varepsilon W} = 4$, $C_{P\varepsilon W} = 1.5$, and $C_{P\varepsilon W} = 3.24$.

475 2.4. Combustion Modeling

476 Near the fire front and due to the presence of hot spot (hot gases, burning particles, etc.),
 477 CO gas and soot particles resulting from the decomposition of the vegetation react with the
 478 ambient air to produce CO₂ gas according to the following equations written for 1kg of fuel.



479 where $\nu_{O_2}^G = 4/7$ and $\nu_{O_2}^{Soot} = 8/3$ are the mass stoichiometric ratios.

480 Typical in gaseous combustion, the rate of consumption of CO gas is limited by two physical
 481 processes: at a small scale, by the time necessary for the chemical reaction to occur and, at
 482 a larger scale, by the time required for an effective mixing between the gaseous fuel and the
 483 ambient air. The rate of reaction governed by chemical kinetics is evaluated from an
 484 Arrhenius law as [34–36]:

$$\overline{\dot{\omega}_{CO}^{Ar}} = \bar{\rho}^2 \tilde{Y}_{CO} \tilde{Y}_{O_2} K_{Ar} \exp(-E_{Ar}/R_0 \tilde{T}) \quad (49)$$

485
 486
 487
 488
 489 where the pre-exponential factor $K_{Ar} = 7 \times 10^4$ m³/kg.s and the ratio of the activation energy
 490 with the ideal gas constant $E_{Ar}/R_0 = 8000$ K. On the other hand, the mixing between the
 491 gaseous fuel (CO) and the ambient air is mainly piloted by the turbulent eddies located in
 492 the flaming zone. If the conditions are fully turbulent, the reaction rate can be written as a
 493 function of the local mass of reactants available for burning divided by the turbulent time
 494 scale (eddy dissipation combustion concept) [34]:

$$\overline{\dot{\omega}_{CO}^{EDC}} = C_A \bar{\rho} / \tau_{mix} \times \text{Min}(\tilde{Y}_{CO}, \tilde{Y}_{O_2} / \nu_{O_2}^G) \quad (50)$$

497 The parameter C_A depends on the turbulent Reynolds number and is given by [34]:

$$C_A = \frac{23.6}{Re_T^{0.25}} \frac{\chi}{(1 - \chi\gamma)} \quad (29)$$

498 where γ is the volume fraction of the small-scale turbulent structures and χ is the fraction
499 occupied by the reaction zone inside these small structures, defined as follows:

$$\gamma = 9.7 Re_T^{-0.75} \quad \chi = \frac{Re_T^{0.25}}{2.13} \frac{\tilde{Y}_{CO_2}/(1 + \nu_{O_2}^G)}{\tilde{Y}_{CO} + \tilde{Y}_{CO_2}/(1 + \nu_{O_2}^G)} \quad (30)$$

500 The turbulent time scale τ_{mix} is the maximum between the integral turbulence time scale
501 (k/ε) and $6\tau_\eta$, where $\tau_\eta = (\bar{\mu}/\bar{\rho}\varepsilon)^{1/2}$ is the Kolmogorov time scale.

502 The rate of combustion of the gaseous fuel is finally obtained from:
503

$$\overline{\dot{\omega}_{CO}} = -\text{Min}(\overline{\dot{\omega}_{CO}^{EDC}}, \overline{\dot{\omega}_{CO}^{Ar}}) \quad (53)$$

504 Consequently, the rates of destruction of O_2 and of formation of CO_2 resulting from the
505 combustion of CO are according to Eq. (27): $\overline{\dot{\omega}_{O_2}^G} = \nu_{O_2}^G \overline{\dot{\omega}_{CO}}$ and $\overline{\dot{\omega}_{CO_2}^G} = -(1 + \nu_{O_2}^G) \overline{\dot{\omega}_{CO}}$.

507 Because of the lack of information on soot production in natural fire, the production rate of
508 soot is limited to that resulting from the pyrolysis process [7] given by Eq. **Error!**
509 **Reference source not found.** Assuming that the soot particles can be assimilated as
510 carbon spheres of diameter $d_{soot} = 1 \mu\text{m}$ and density $\rho_{soot} = 1800 \text{ kg/m}^3$, the soot volume
511 fraction field \tilde{f}_v is evaluated from the following transport equation [36, 37]:
512

$$\frac{D(\bar{\rho}\tilde{f}_v)}{Dt} = -\frac{\partial}{\partial x_j} (\bar{\rho} \tilde{u}_j^{th} \tilde{f}_v) - \frac{\partial}{\partial x_j} (\rho u_i' f_v') + \overline{\dot{\omega}_\alpha} + \frac{\bar{\rho}}{\rho_{soot}} \sum_m (M_{soot}^m - \overline{\dot{\omega}_{soot}}) \quad (54)$$

513
514 We can notice that the transport of the soot particles by convection is enhanced by the
515 temperature gradient (thermophoretic velocity \tilde{u}_j^{th}) defined by:
516

$$\tilde{u}_j^{th} = -0.54 \frac{\bar{\mu}}{\bar{\rho}} \frac{\partial(\ln \tilde{T})}{\partial x_j} \quad (31)$$

517 The term $\overline{\dot{\omega}_{soot}}$ results from soot oxidation and is evaluated from the rate for oxidation of
518 pyrolytic graphite by O_2 as follows [36]:
519

$$\overline{\dot{\omega}_{soot}} = 12 \tilde{f}_v \sigma_{soot} \left[\frac{k_A \bar{P}_{O_2}}{1 + k_z \bar{P}_{O_2}} \zeta + k_B \bar{P}_{O_2} (1 - \zeta) \right] \text{ with } \zeta = (1 + k_T/k_B \bar{P}_{O_2})^{-1} \quad (56)$$

520
521

522 where $\sigma_{soot} = 6/d_{soot}$ is the surface area-to-volume ratio of soot particles, P_{O_2} is the partial
 523 pressure of oxygen, and the various reaction rates k_A , k_B , k_T , and k_z depend on temperature
 524 according to Arrhenius laws [36]. The rates of destruction of O_2 and of formation of CO_2
 525 resulting from the soot oxidation are estimated according to Eq. (28): $\bar{\omega}_{O_2}^{soot} = -v_{O_2}^{soot} \bar{\omega}_{soot}$
 526 and $\bar{\omega}_{CO_2}^{soot} = (1 + v_{O_2}^{soot}) \bar{\omega}_{soot}$.

527

528 2.5. Radiation Heat Transfer

529 Radiation is one of the most important heat transfer mechanisms contributing to the
 530 propagation of a fire. It usually represents about 30% of the energy received by the
 531 vegetation located ahead of the fire front [20]. The total irradiance J is calculated by
 532 integrating the radiation intensity I in every direction:

$$J = \int_0^{4\pi} I d\Omega \quad (32)$$

533 Radiation mainly results from soot particles produced in the flame and from the embers
 534 located behind the fire front. Accounting for these two contributions, the variation of the
 535 radiative intensity I along an optical path s verifies the following radiation transfer
 536 equation where σ_G is the absorption coefficient of the gas-soot mixture.

$$\frac{d(\alpha_G I)}{ds} = \alpha_G \sigma_G \left(\frac{\sigma \tilde{T}^4}{\pi} - I \right) + \sum_m \frac{\alpha_s^m \sigma_s^m}{4} \left(\frac{\sigma (T_s^m)^4}{\pi} - I \right) \quad (33)$$

537 The absorption coefficient σ_G depends on the amounts of evaporation and combustion
 538 products (CO_2 and H_2O), on the gas mixture temperature, and of the soot volume fraction
 539 [39] according to the following relation:

$$\sigma_G = 0.1 (\tilde{X}_{CO_2} + \tilde{X}_{H_2O}) + 1862 \tilde{f}_v \tilde{T} \quad (34)$$

540 where \tilde{X}_{CO_2} and \tilde{X}_{H_2O} are the mole fractions of CO_2 and H_2O respectively. A method adapted
 541 to optically thick media (very sooty flames), as well as to quasi-transparent media must be
 542 used to solve the radiation transfer equation (see next section).

543 3. Numerical Method

544 Describing the details of the numerical method used in FireStar3D is beyond the scope of
 545 this paper; only the outlines of the method are presented in this section, as well as the
 546 numerical improvements brought to the 2D version of the computational code (namely
 547 FireStar2D). Two independent meshes are used to solve the mathematical model: a first
 548 one for the gaseous phase and a second one for the solid phase (vegetation).

549 The transport equations in the gaseous phase **Error! Reference source not found.** to (11),
 550 (23), (24), and **Error! Reference source not found.** are solved numerically in a
 551 rectangular domain by a fully-implicit finite volume method using a segregated formulation
 552 [38] on a structured and non-uniform staggered-mesh. To avoid fire extinction within the

553 solid-fuel bed for radiation-dominated fire propagation, the upper limit of the grid size (Δ_x ,
554 Δ_y , Δ_z) is given by [15] (both in the gas and the solid phase):

$$\text{Max}(\Delta_x, \Delta_y, \Delta_z) < 4 \sqrt{\sum_m \alpha_s^m \sigma_s^m} \quad (35)$$

555 where $4/\alpha_s^m \sigma_s^m$ is the extinction length scale within the solid-fuel bed corresponding to
556 vegetation family m . Previous simulations performed in worst conditions of propagation
557 [41, 42], where the air flow was opposite to the direction of propagation, had shown that
558 the verification of this criterion (60) near the fire front was sufficient to ensure a correct
559 estimation of the heat transfer by radiation between the fire front and the solid fuel, and
560 consequently to obtain grid-size-independent numerical results. On the other hand, the size
561 of any cell adjacent to the wall should carefully be chosen such that its center fall within the
562 log-law region of a turbulent boundary layer [40] where the rate of turbulence production
563 equals the rate of dissipation (equilibrium turbulence). This condition is fulfilled if
564 dimensionless distance to the wall of the cell center defined by Eq. (61) satisfies the
565 constraint $11.5 < y^+ < 500$, and this during the entire simulation time.

$$y^+ = \frac{\bar{\rho} C_\mu^{1/4} k^{1/2} y}{\mu} \quad (36)$$

566 Wall-function formulae [40] covering both the viscous sub-layer and the log-law region
567 were then used to estimate wall shear-stresses and fluxes. An important improvement
568 brought to the 2D version is space and time discretization. The first-order fixed-time step
569 time discretization of the 2D version was replaced by a third order Euler scheme with
570 variable time steps. The time steps are obtained from an adaptive time stepping algorithm
571 based on the estimation of the truncation error [43]. The second-order space discretization
572 was replaced by the third order QUICK scheme [44] with flux limiters for convection terms,
573 while diffusion terms were approached by central difference [40]. This improvement
574 results in a higher accuracy or in larger time steps and a coarser mesh for a desired
575 accuracy (specified by a prescribed truncation error). It also allows the time step to varie
576 automatically between two prescribed limits according to the characteristic time scale of
577 the predominant physics. Since the momentum and the continuity equations are solved
578 separately, the coupling between the velocity field and the pressure field is ensured using a
579 PISO algorithm [45]. The linear systems resulting from the discretization of the transport
580 equations are solved using a bi-conjugate gradient stabilized method with Jacobi
581 preconditioner [46], while pressure equation is solved using a conjugate gradient method
582 with implicit modified ILU (MILU) preconditioner [47]. This is another important
583 improvement brought to the 2D version of the computational code, which decreases by a
584 factor 5 to 6 the CPU time required to solve the pressure equation that consumed in the
585 previous works [8-10] more than 70% of the total CPU time. In addition, the pressure
586 equation is preconditioned using the artificial compressibility method [48]. The radiative
587 transport equation (58) is solved using a Discrete Ordinate Method, consisting in the

588 decomposition of the radiation intensity in a finite number of directions and a Gauss-
589 Legendre quadrature [49].

590 Embedded in the fluid domain, the solid-phase domain is also subdivided into solid-fuel
591 elements using a rectangular uniform mesh. Each element could contain several vegetation
592 families, and the state of each family m is characterized by its own set of variables: α_S^m , ρ_S^m ,
593 M^m , σ_S^m , composition, etc. As indicated previously, the size of the solid-phase mesh (Δ_x^S , Δ_y^S ,
594 Δ_z^S) is also chosen according to Eq. (35), and Eqs. **Error! Reference source not found.** to
595 **Error! Reference source not found.** are solved for each vegetation family m and for each
596 solid-fuel element separately using a fourth-order Runge-Kutta method (RK4).

597 From the implementation point of view, the solver was parallelized [47] and optimized [50]
598 using the APIs OpenMP and HMPP directives (suitable for shared memory platforms). This
599 is another feature specific to FireStar3D by comparison with its 2D counterpart. FireStar3D
600 is operational on high-performance computing machines consisting of a SMP node using
601 modern processors with INTEL Xeon Phi co-processors and NVIDIA graphic cards. The
602 Navier-Stokes low-Mach-number solver of FireStar3D has been extensively validated on
603 several benchmarks of laminar and turbulent natural convection and forced convection
604 including non-Boussinesq effects [50], and the multiphase part was tested for neutrally
605 stratified atmospheric flow within and above a sparse forest canopy [51].

606

607 **4. Fire Propagation in Wind Tunnel**

608 After testing the hydrodynamic and the multiphase modules of FireStar3D on academic
609 configurations [50, 51], the first validation of the entire model was performed by
610 simulating some experimental fires conducted in the wind-tunnel of Missoula Fire Sciences
611 Laboratory [12]. This choice can be justified by the fact that these experiments were
612 conducted under well-controlled experimental conditions that guaranteed a good
613 reproducibility of the results [12], this concerns both the structure and the state of the
614 fuelbed (homogeneity, depth, moisture content, density, load ...) and the turbulent flow in
615 the wind tunnel. As indicated by Catchpole et al. [12], the length of the test section (8 m)
616 was long enough to reach a quasi-steady state of fire propagation, and over 4.5 m of
617 propagation, the variation of the rate of spread was about 10%, which can be considered as
618 satisfactory. 15 duly chosen experiments of fuelbed fire carried out by Catchpole et al. [12]
619 were reproduced numerically. The comparison between the numerical results and the
620 experimental data was limited to the rate of spread since this was the only available output
621 from these experiments. Nevertheless, this integral variable can be considered a good
622 indicator of the overall fire behavior. Also, at low fuel moisture content (less than 20%), all
623 the solid fuel was consumed, thus the knowledge of the rate of spread allows also to
624 evaluate the fire intensity.

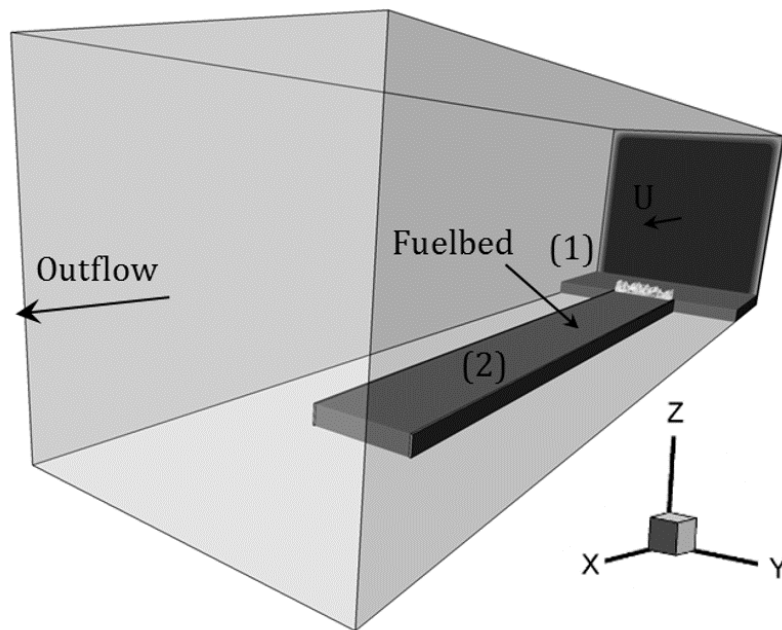
625 **4.1. Fuelbed Configuration**

626 As shown in Fig. 1, the fuelbed was divided into two zones having the same physical
 627 characteristics; however, only zone (2) was thermally degradable, i.e. equations **Error!**
 628 **Reference source not found.** to **Error! Reference source not found.** of the solid-fuel
 629 model were only solved for zone (2). Zone (1) (2m long) was added to account for a wire
 630 mesh spoiler used in the experiment and placed transversely on the floor of the wind
 631 tunnel to initiate more rapidly the turbulent boundary layer flow [12]. Also, vertical strips
 632 of metal sheeting (matching the fuelbed height) were placed in the experiments along each
 633 side of the tray to mimic a wider fire front by preventing in-drafts into the combustion
 634 zone. These strips were accounted for numerically by placing vertical baffles along each
 635 side of the fuelbed (see Fig. 1); the velocity component normal to the baffles (y component)
 636 was set to zero, while a friction coefficient $C_f = 0.01$ was introduced in the momentum
 637 equations of the velocity components tangential to the baffles (x and z components). This
 638 friction coefficient is twice that of a turbulent flow over a smooth flat plate (to account for
 639 both sides of the baffles) at a Reynolds number of about 5×10^5 . Nevertheless, doubling the
 640 value of C_f or dividing it by 2 had no noticeable effect on the fires dynamics.

641 Before ignition, simulations were run long enough using Neumann conditions at the open
 642 boundaries while imposing a negative artificial pressure gradient in the x -momentum
 643 equation. This artificial pressure gradient was adjusted automatically by the solver in order
 644 to reach at each time step the desired wind speed at the center of the wind tunnel entrance
 645 that was imposed in the experiment. This phase was maintained for 5 seconds, which was
 646 the time required for reaching a quasi-steady turbulent flow. Then, the turbulent velocity
 647 profile, obtained at the wind tunnel entrance, was applied at the inlet of the domain during
 648 the remaining time of simulation. At $t = 5$ s, fire was set at the entrance of zone (2) by
 649 injecting carbon monoxide at 1600 K from the bottom of the computation domain for
 650 another 5 seconds (hence reproducing a porous gas burner). The injection surface lies
 651 between $x = 2$ m and $x = 2.16$ m, and along the entire width of zone (2). According to the
 652 equation (62), at $t = 5$ s the average injection speed is maximum ($V_j = 10$ cm/s), then it
 653 decreases linearly with the burned mass of dry material (m_b) in order to avoid destabilizing
 654 the fire-front by suddenly ceasing the injection.

$$V_j (\text{cm} / \text{s}) = 10 \times (1 - m_b / m_{b0}) \quad (37)$$

655 where m_{b0} is the initial mass of dry material located above the burner (i.e. the mass of dry
 656 material inside the volume $V_{b0} = 0.16 \times 1 \times \delta \text{ m}^3$). Equation (62) was used between $t = 5$ s and
 657 $t = 10$ s as long as V_j had remained positive, but the injection of carbon monoxide was
 658 stopped once V_j had reached zero during this time interval.



659

Fig. 1. Perspective view of the computation domain corresponding to Catchpole et al. experiment. The flow domain dimensions are $12 \times 3 \times 3 \text{ m}^3$ and those of the fuelbed are $10 \times 1 \times \delta \text{ m}^3$ (the fuelbed thickness $\delta = 15.2$ or 20.3 cm). The fuelbed is divided into two zones, only zone (2) ($2 \text{ m} < x < 10 \text{ m}$) is thermally degradable, vertical baffles (0.25 m high) are placed along both sides of zone (2) and fire is set at its entrance.

660

661 The simulations were conducted for three types of solid fuel, namely: Populus tranulos -
 662 regular excelsior (dry material density $\rho_{Dry} = 398 \text{ kg/m}^3$, surface-to-volume ratio $\sigma_S = 7596$
 663 m^{-1} , and pyrolysis heat release $\Delta h_{Pyr} = 711 \text{ kJ/kg}$), Populus tranulos - coarse excelsior (ρ_{Dry}
 664 $= 398 \text{ kg/m}^3$, $\sigma_S = 3092 \text{ m}^{-1}$, and $\Delta h_{Pyr} = 711 \text{ kJ/kg}$), and Pinus ponderosa heartwood sticks
 665 ($\rho_{Dry} = 442 \text{ kg/m}^3$, $\sigma_S = 630 \text{ m}^{-1}$, and $\Delta h_{Pyr} = 659 \text{ kJ/kg}$). This choice allowed to cover both
 666 the fine fuel case and the threshold fine/coarse fuel one. The simulations correspond to
 667 experiments EXMC 23, 24, 28, 36, 48, 5I, 69, 82, EXSC 64, 65, 73, 7D, and MF 37, 38, 54
 668 carried out by Catchpole et al. [14]. These 15 experiments, whose main physical data are
 669 shown in Tab. 2, were chosen to test the dependence of the ROS on wind speed U and on
 670 the fuelbed characteristics (fuel type, fuel moisture-content M , solid-fuel volume-fraction
 671 α_S , and fuelbed depth δ). These experiments were also selected to obtain a wide range of
 672 fuelbed optical thickness, defined as the ratio between the depth of the fuelbed and the
 673 extinction length scale $\tau_{opt} = \alpha_S \sigma_S \delta / 4$, that varies by an order of magnitude. Finally, it should
 674 be noted for the MF series (Pinus ponderosa heartwood sticks) that $\sigma_S = 630 \text{ m}^{-1}$
 675 corresponds to cylindrical particles having an average diameter of 6.3 mm , which is about
 676 the threshold size between thermally thin and thick particles.

677

678

		α_s	δ (m)	U (m/s)	M (%)	τ_{opt}
1	EXMC23	0.005	0.203	2.68	5.5	1.93
2	EXMC24	0.005	0.203	0.89	5.2	1.93
3	EXMC28	0.005	0.203	1.79	5.4	1.93
4	EXMC36	0.005	0.203	2.68	10.1	1.93
5	EXMC48	0.005	0.203	2.68	18.1	1.93
6	EXMC51	0.005	0.152	2.68	4.5	1.44
7	EXMC69	0.005	0.203	2.68	3.0	1.93
8	EXMC82	0.015	0.203	1.79	4.9	5.78
9	EXSC64	0.010	0.152	1.34	4.1	1.17
10	EXSC65	0.015	0.203	2.68	3.1	2.35
11	EXSC73	0.015	0.203	2.68	23.6	2.35
12	EXSC7D	0.015	0.203	1.34	7.5	2.35
13	MF37	0.018	0.152	0.89	6.5	0.43
14	MF38	0.018	0.152	2.68	6.2	0.43
15	MF54	0.009	0.152	2.68	5.9	0.22

679

Tab. 2. Catchpole et al. experiments chosen to show the effect of solid-fuel characteristics, of fuelbed height, and of wind speed on fire spread dynamics. EXMC series: Populus tranulos (regular excelsior), EXSC series: Populus tranulos (coarse excelsior), MF series: Pinus ponderosa heartwood sticks. δ - fuelbed depth, U - wind speed, α_s - solid-fuel volume fraction, M - fuel moisture content, τ_{opt} - fuelbed optical thickness.

680

681 As indicated in a previous section, a uniform mesh was used for the solid domain with a
682 grid size $(\Delta_x^S, \Delta_y^S, \Delta_z^S) = (2 \text{ cm}, 1.25 \text{ cm}, 1.69 \text{ cm})$, while a wall-refined mesh of $300 \times 80 \times 62$
683 grid points was used for the fluid domain. Within the vegetation zone, the fluid-domain
684 mesh was uniform and twice coarser (in each direction) than the solid-domain mesh,
685 whereas it was gradually refined toward the rigid walls according to geometric
686 progression. The grid size of the fluid-domain varied between 2.5 cm and 8.7 cm, while the
687 value of $4/\alpha_s \sigma_s$, representing the extinction length scale within the fuelbed, varies from
688 3.51 cm (for EXMC82) to 70.5 cm (for MF54); hence, the constraint given by Eq. (35) is
689 respected in all directions for all simulations. For the adaptive time-stepping strategy, the
690 minimum and maximum time-step values were set to 10^{-3} and 10^{-2} s respectively, and the
691 desired level of truncation error was set to 10^{-4} . Finally, at each time step, the global
692 convergence was assumed to be reach when the L_2 -norms of all transport equations
693 residuals had reached 10^{-5} in normalized form and 10^{-4} in non-normalized form. Typically,
694 30 seconds of simulation time required in average 96 hours of CPU time on a 16-processor
695 shared-memory workstation.

696

697

698 **4.2. Results and Discussion**

699 Figure 2 shows the gas temperature and the flow structure (streamlines), obtained
700 numerically 15 s and 25 s after ignition in the case of experiment EXMC23. We notice the
701 strong 3D effects characterizing the behavior of the fire, with a head of the fire front
702 structured as a tip and the gas flow bypassing laterally the flaming zone (clearly shown at
703 $t = 20$ s and $t = 30$ s in the horizontal plane). We also notice (in Fig. 2-b in the vertical
704 median plane) the existence of a reverse flow, drawing in fresh air from the wind-tunnel
705 exit into the flaming zone; this shows the potential of FireStar3D in handling backflow
706 situation (i.e. as in the experiments, the exit of the wind-tunnel was not treated as an
707 imposed outflow boundary conditions, the model allows for a backflow to occur at the exit
708 of the wind-tunnel as a result of the mass balance). This feature must be underlined, it can
709 be very appreciable in simulating some particular situations, such as fires propagating in
710 no-wind conditions, back-fires, and counter-fires. In comparison, the outflow conditions in
711 FIRETEC are forced to match the inlet conditions calculated before fire ignition, thus
712 violating the total mass balance for not accounting for the additional mass source resulting
713 from the decomposition of the solid fuel and for the modifications induced on the flow by
714 the development of the thermal plumes [52]. The procedure used in Firestar3D is thus
715 similar to that used in WFDS; this difference in handling outflow conditions, between
716 FireStar3D/WFDS on one hand and FIRETEC on the other, can explain the difference in
717 efficiency between these 3D codes and in their ability to simulate some particular
718 configurations, such as backfire situations [52,53].

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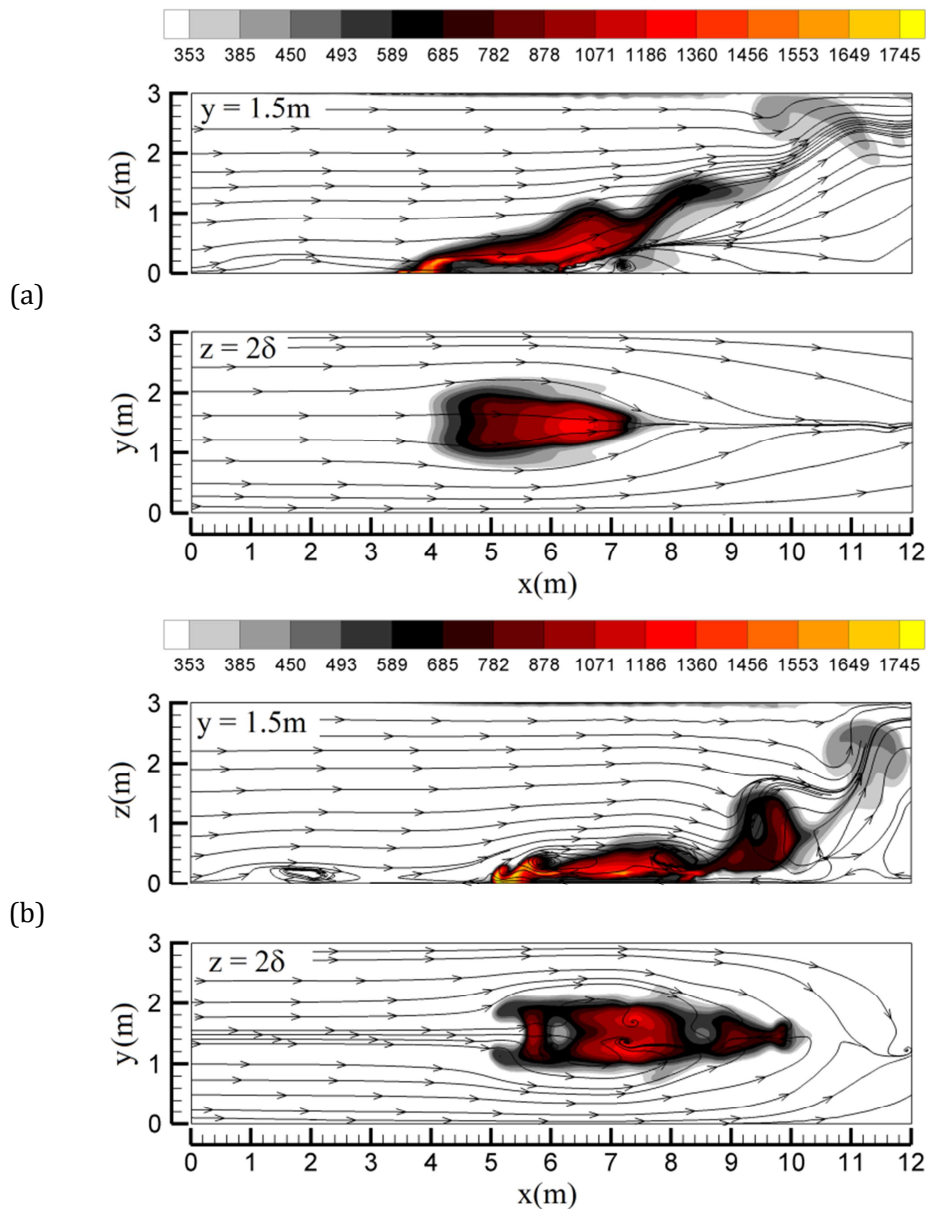
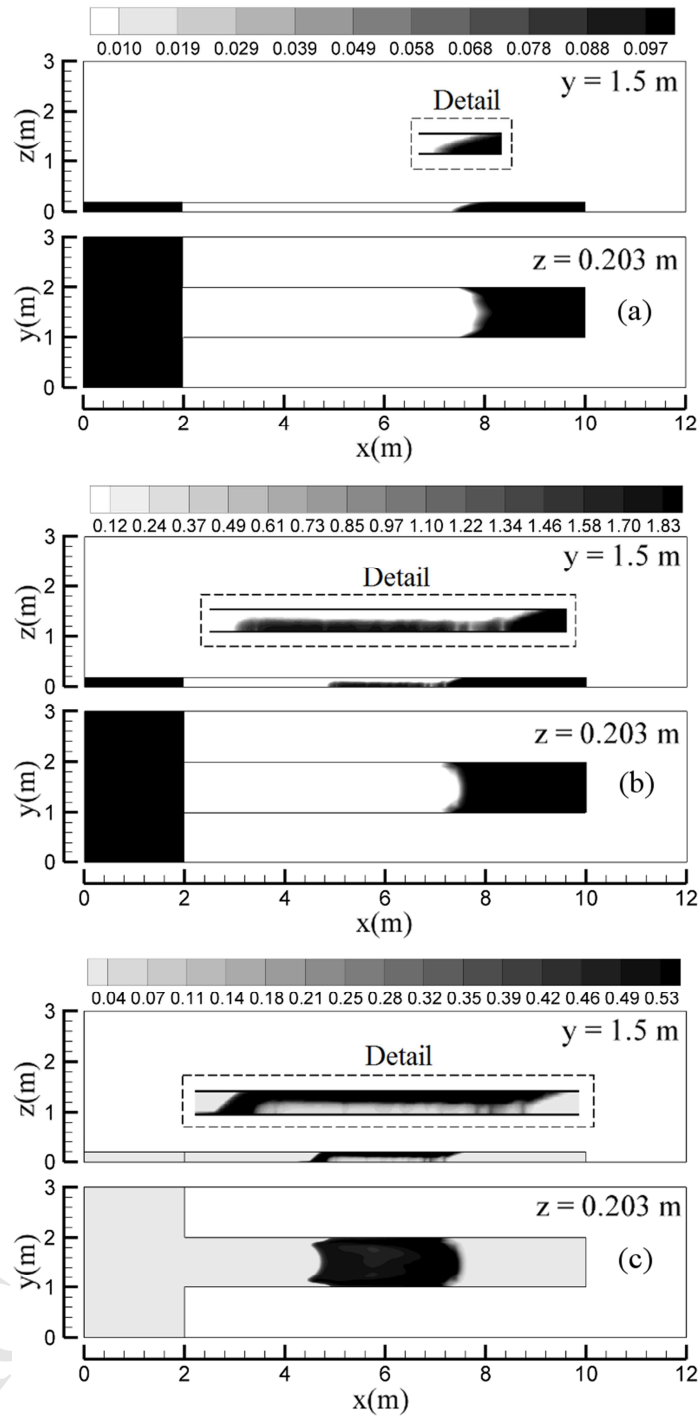


Fig. 2. Temperature fields and streamlines obtained numerically at $t = 20$ s (a) and at $t = 30$ s (b) in the case of experiment EXMC23 of Catchpole et al. [12] (regular excelsior, wind speed of $U = 2.68$ m/s, moisture content $M = 5.5\%$, see Tab. 2 for more details). Top: solution in the vertical median plane ($y = 1.5$ m), bottom: solution in the horizontal plane at $z = 2\delta$.

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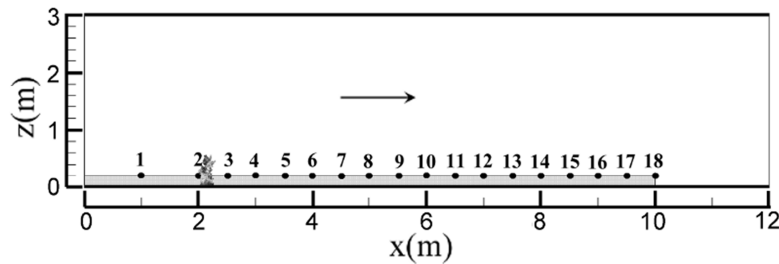
Fig. 3. Distributions of the solid-fuel composition in effective density (kg/m^3) at the surface of the fuelbed ($z = 0.203 \text{ m}$) and in the vertical median plan ($y = 1.5 \text{ m}$), obtained at $t = 25 \text{ s}$, corresponding to experiment EXMC23 of Catchpole et al. [12] (see Tab. 2 for details): (a) water $\rho_S^e Y_{H_2O}$, (b) dry fuel (wood) $\rho_S^e Y_{Dry}$, and (c) charcoal $\rho_S^e Y_{Char}$.

729

730 Figure 3 reports the distributions of solid-fuel composition (in terms of effective density of
731 water, dry fuel and charcoal) within the fuelbed. We notice that while the dehydration
732 process took place in the entire depth of the fuelbed (Fig. 3-a), the pyrolysis process was
733 characterized with more inertia, it took place within the upper layer of the fuelbed first
734 (Figs. 3-b and 3-c), before affecting the whole solid-fuel layer. This result is closely related
735 to the relative high value of the fuelbed optical thickness ($\tau_{opt} = 1.93$ for experiment
736 EXMC23); in this case, the solid fuel depth was about twice larger than the extinction length
737 scale at which the radiation from the flame was absorbed. Whereas, for the same reasons
738 detailed just above, the pyrolysis process took place within the entire depth of the fuelbed
739 in the case of experiment MF54 ($\tau_{opt} = 0.215$). The burning area at the surface of the fuelbed
740 can be easily determined in Fig. 3-c from the distribution of charcoal mass-fraction, it
741 extends approximately from 4.4 m to 7.6 m. We can notice that at the end of charcoal
742 combustion process (Fig.3-c) the totality of the fuel was consumed, which was effectively
743 observed for this kind of experiment.

744
745 The comparison between the simulations and the experimental data was based on the rate
746 of spread of fire or ROS (i.e. the average velocity of the pyrolysis front). For this purpose,
747 fuelbed characteristics were monitored at the surface of the fuelbed at several positions
748 along the direction of propagation of the fire ($y = 1.5$ m, $z = 0.203$ m) as shown in Fig. 4, by
749 analogy to the photocell tubes positioned at 0.5 m intervals in the experiments [12]. Figure
750 5 shows the time evolution of the fuelbed temperature at duly chosen points of Fig. 4; we
751 clearly notice the phase of pyrolysis (between 400 K and 500 K according to the model)
752 followed by the passage of the gaseous combustion front, the char combustion and the
753 cooling phase at the back of the fire. The ROS could be easily estimated from Fig. 5 by
754 measuring the average time required for the pyrolysis front (isotherm 500 K) to move from
755 a monitoring point to another (covering each time a fixed distance), in this case it was
756 equal to 0.258 m/s. By comparing Fig. 3-c (obtained at $t = 25$ s) with the time history of the
757 solid-fuel temperature shown in Fig. 5, and if we focused our analysis on point 8, we notice
758 that the solid fuel is relatively hot (around 900 K) due to the arrival of the flame front at
759 $t = 15$ s (the ignition is clear with a sudden increase of temperature beyond 500 K). Then at
760 $t = 28$ s, the curve of the solid-fuel temperature is characterized by a sharp peak that lies
761 between 2000 K and 2250 K. If we multiply the time gap (13 s) between these two events,
762 by the average ROS (0.258 m/s), we obtain a distance of 3.3 m, which is more or less equal
763 to the length of the charcoal region in Fig. 3-c. Despite the coarse nature of this analysis, it
764 seems evident that the peak of temperature was due to an event occurring at the end of the
765 charring combustion. The temperature peak (2000 – 2250 K) is not the result of heat
766 transfer from the gas phase since, as shown by Fig. 6, the gas temperature at the same
767 point, 8, does not exceed 1800 K, which is in agreement with the values measured
768 experimentally in the persistent flame above a forest fuel burner [52]). The temperature
769 peak is the result of thermal equilibrium of the solid-fuel particle, when the combustion

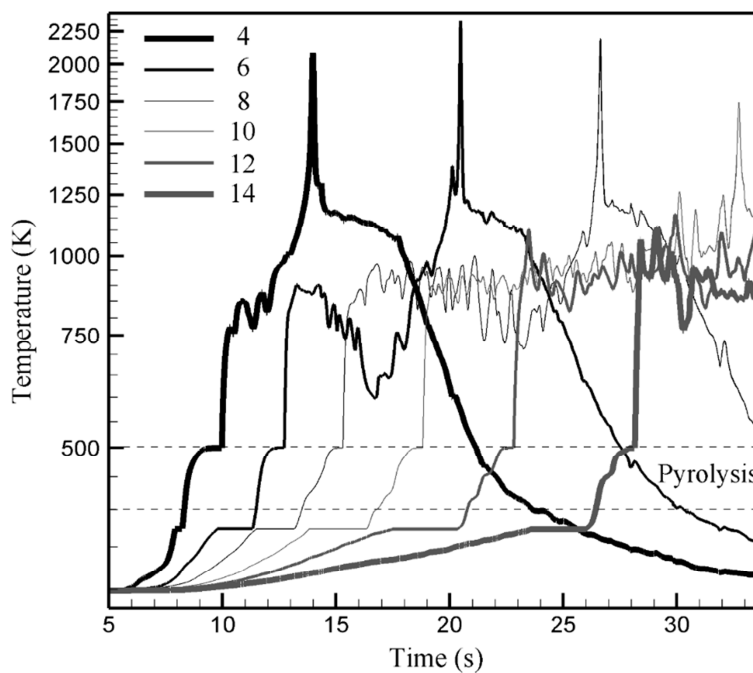
770 energy partially absorbed by the particle (given by Eq. 8) is entirely evacuation by
 771 convection and radiation according to Eq. 16. The relatively short duration of this peak ($T >$
 772 1200 K for about 0.54 s) suggests that it occurs during the final regression phase of solid-
 773 fuel particles from charcoal to ashes clearly shown in Fig. 7 by charcoal density. A closer
 774 view of Fig. 7 shows that, during the final step of the regression phase, the charcoal density
 775 decreased from 0.4 kg/m^3 the dry fuel located above the burner to 0 in 0.38 s .



776

Fig. 4. Positions in the vertical median plan of the computation domain ($y = 1.5\text{ m}$) where fuel characteristics are monitored during the simulations of Catchpole et al. experiments [12].

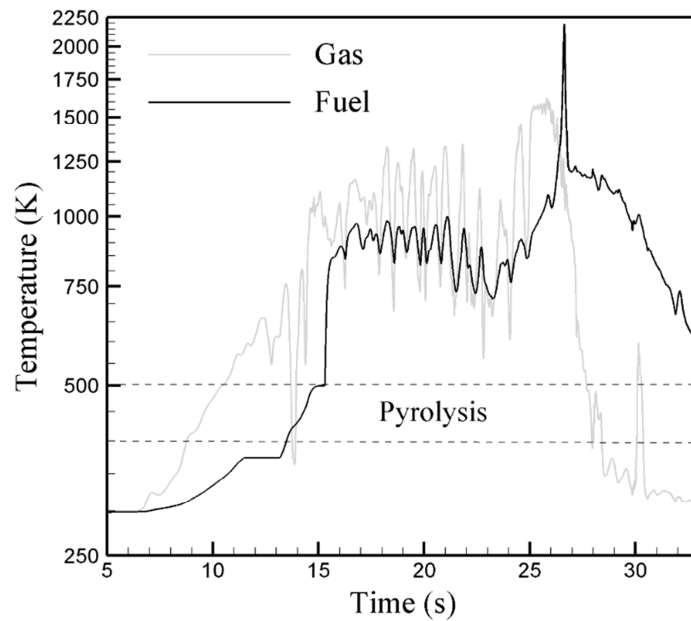
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Fig. 5. Time-evolution of the solid fuel temperature (semi-logarithmic scale) at positions 4, 6, 8, 10, 12, and 14 of Fig. 4, corresponding to experiment EXMC23 of Catchpole et al. [12] (see Tab. 2 for details).

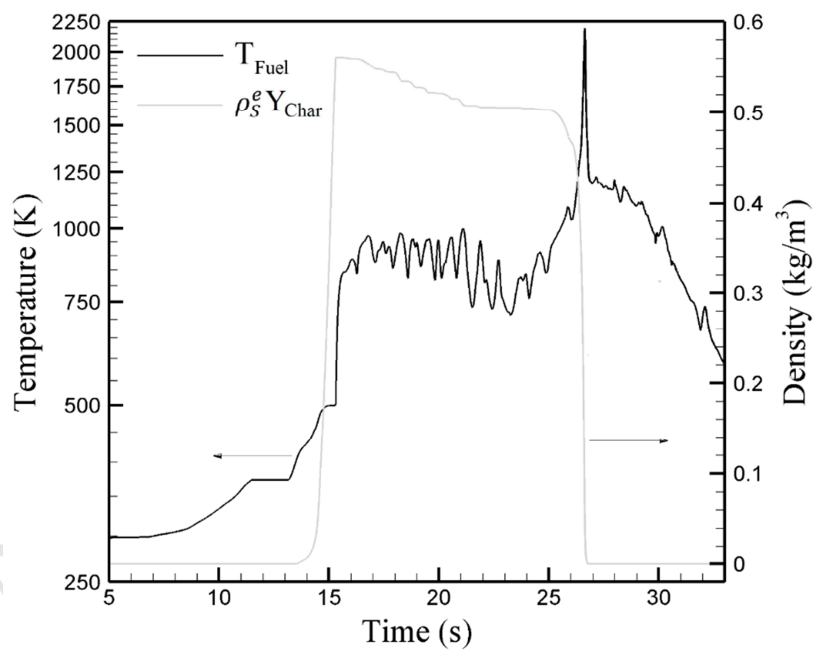
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Fig. 6. Time-evolution of the solid fuel and gas temperatures at positions #8 of Fig. 4, corresponding to experiment EXMC23 of Catchpole et al. [12] (see Tab. 2 for details).

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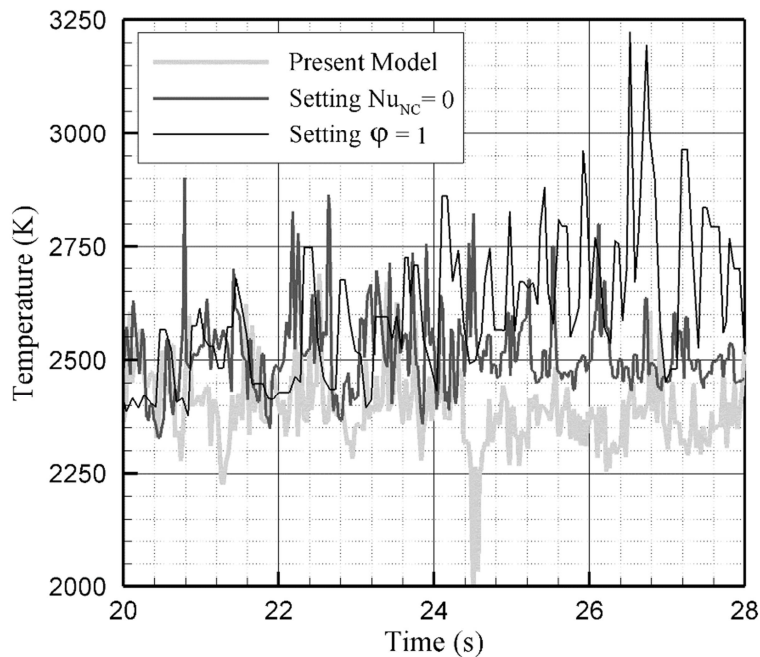


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Fig. 7. Time-evolution of the solid-fuel temperature and the bulk charcoal density at positions #8 of Fig. 4, corresponding to experiment EXMC23 of Catchpole et al. [12] (see Tab. 2 for details).

783

784 Two main improvements were brought to FireStar3D model compared to previous works
 785 [8-10]: (i) accounting for incomplete combustion in the solid phase through variable φ
 786 given by Eq. 5 that continuously varies with temperature between 0.5 (only CO is
 787 produced) and 1 (only CO₂ is produced), (ii) accounting for natural convection in the
 788 expression of the Nusselt number given by Eq. 18. As shown by Fig. 8, both these new
 789 features result in a significant reduction of the maximum fuelbed temperature and
 790 consequently of the peak reached by the solid-particle temperature. Indeed, as mentioned
 791 before, the temperature peak is the result of thermal equilibrium of the solid-fuel particle.
 792 On one hand, accounting for incomplete combustion in the solid phase decreases ΔH_{char}
 793 (given by Eq. 9) and consequently the energy partially absorbed by the particle (given by
 794 Eq. 8); on the other hand, accounting for natural convection increases the convection heat
 795 transfer coefficient h_s (given by Eq. 17) and consequently the capacity of the particle to
 796 evacuate the absorbed energy according to Eq. 16.
 797



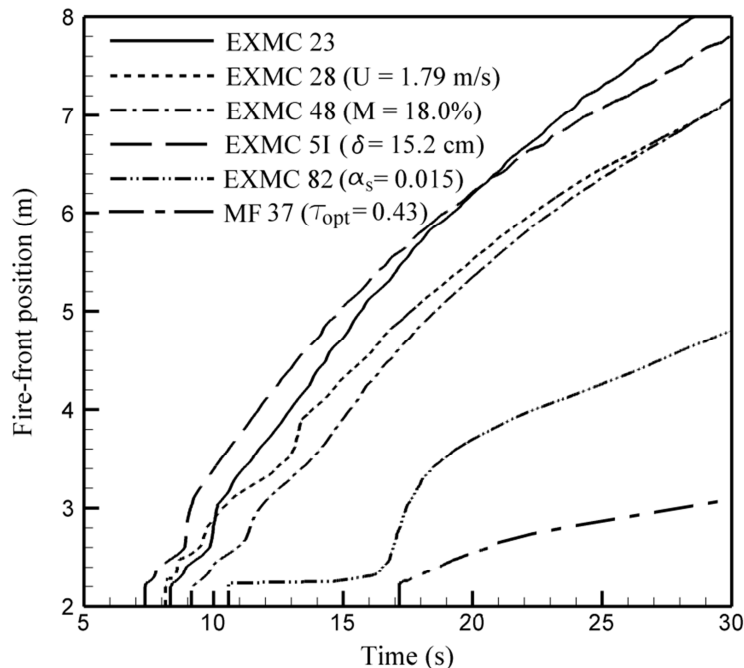
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Fig. 8. Time-evolution of the maximum fuelbed temperature in experiment EXMC23 of Catchpole et al. [12] (see Tab. 2 for details) obtained (i) using the present improved model, (ii) by setting $Nu_{NC} = 0$ in Eq. 18, and (iii) by setting $\varphi = 1$ in Eqs. 4 and 9.

799

800 A simpler and more accurate method for estimating the ROS consists in finding at each time
 801 step of simulation the average position of the pyrolysis front at the fuelbed surface. This
 802 was done by determining the average position of the most remote points at the fuelbed
 803 surface and downstream the burner that are characterized by zero dry fuel (wood) mass
 804 fraction. In Fig. 3-b, we clearly distinguish the pyrolysis front, it corresponds to the

805 interface located at about $x = 7.6$ m. Figure 9 shows the time evolution of the pyrolysis-
 806 front positions for duly chosen simulations. We notice, as expected, that increasing the
 807 wind speed U or decreasing the solid-fuel moisture-content M or volume-fraction α_s
 808 increases the rate of fire spread. However, the fuelbed depth has no significant influence on
 809 the ROS, in agreement with experimental observations [12]. We can also notice that for two
 810 tests (EXMC 82 and MF37), the dry fuel located above the burner did not fully burn at the
 811 end of the ignition phase (which occurs between time equal 5 s and 10 s and according to
 812 Eq. 62), this explains the time lag in Fig. 9 observed for these two tests. We also notice that
 813 in the case of fast fire spreads obtained for a sparse solid-fuel bed ($\alpha_s = 0.005$), the fuelbed
 814 length (8 m) was not long enough enable the fire to reach stabilized propagation conditions
 815 (with a constant ROS). Whereas for more dense solid-fuel beds and lower fire rates of
 816 spread, for EXMC 82 ($\alpha_s = 0.015$) and MF 37 ($\alpha_s = 0.018$), a constant value of the ROS was
 817 rapidly reached.
 818



819

Fig. 9. Time-evolution of the average position of the pyrolysis front at the fuelbed surface for duly chosen simulations. For each experiment, the legend reports the parameter that differs significantly from that of experiment EXMC23, showing the effect of several parameters on the rate of fire spread.

820

821 The ROS (average value and standard deviation) was obtained from Fig. 9 by evaluating the
 822 slopes of each curve every 0.5 m, omitting the first 1.5 m (as done experimentally). The fire
 823 rates of spread evaluated numerically were compared to the values measured
 824 experimentally in Fig. 10 and in Tab. 3. On this kind of graph, a point located on the first
 825 diagonal would correspond to perfect numerical prediction of the experimental value. To

826 complete the analysis, we have also reported (both in Fig. 10 and in Tab. 3) the values of
 827 ROS obtained using the correlation given by Eq. (38) that was established by Catchpole et
 828 al. [12] for different fuel types and properties.

$$ROS = \frac{(495.5 + 1934 U^{0.91}) e^{-347/\sigma_s} \alpha_s^{-0.499} e^{-0.73M}}{\rho_{Dry} (\Delta h_{pyr} + M \Delta h_{vap})} \quad (38)$$

829 From values reported in Tab. 3 and in Fig. 10, we can notice that despite the very non-
 830 linear character of this problem, “FireStar3D” predicts correctly the order of magnitude of
 831 the ROS. The general trends observed experimentally between the ROS versus the wind
 832 speed and versus the solid-fuel parameters are correctly reproduced. We notice however
 833 that FireStar3D seems to globally overestimate the ROS, especially in the case of sparse
 834 solid-fuel bed (EXMC24, EXMC28, EXMC36, EXMC48, and EXMC69), for which the predicted
 835 values of the ROS (average and standard deviation) were relatively high, reflecting a very
 836 unsteady fire propagation.

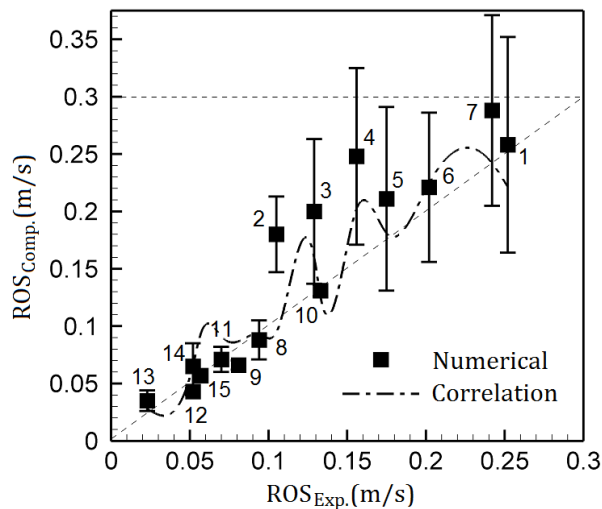
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		Exp.	Simulation	Eq. (38)
1	EXMC23	0.252	0.258±0.094	0.221
2	EXMC24	0.105	0.180±0.033	0.095
3	EXMC28	0.129	0.200±0.063	0.159
4	EXMC36	0.156	0.248±0.077	0.203
5	EXMC48	0.175	0.211±0.080	0.181
6	EXMC51	0.202	0.221±0.065	0.225
7	EXMC69	0.242	0.288±0.083	0.242
8	EXMC82	0.094	0.088±0.017	0.093
9	EXSC64	0.081	0.066±0.004	0.087
10	EXSC65	0.133	0.131±0.005	0.125
11	EXSC73	0.070	0.071±0.011	0.091
12	EXSC7D	0.052	0.043±0.003	0.066
13	MF37	0.023	0.035±0.009	0.028
14	MF38	0.052	0.065±0.020	0.067
15	MF54	0.057	0.057±0.002	0.094

838

Tab. 3. Comparison of the ROS (in m/s) obtained numerically using FireStar3D, experimentally, and using the correlation established in Catchpole et al. given by Eq. (38) for the different experiments shown in Tab. 2.

839



840

Fig. 10. Comparison between the 15 ROS values (from Tab. 3) obtained experimentally, numerically (with variation interval bars), and from Eq. (38) connected by cubic spline. Experiment numbers are shown in Tab. 2 and in Tab. 3.

841

842 The more-or-less unsteady character of fire propagation can be illustrated by comparing
 843 Figs. 2 and 11 obtained for experiments EXMC23 and MF38, respectively. From these two
 844 figures, it is evident that the behavior of the fire was much more unsteady in the case of a
 845 relatively sparse solid-fuel bed (Fig. 2) than for a more than 3 times dense solid-fuel bed
 846 (Fig. 11), with a corresponding increase of the standard deviation of the ROS as shown in
 847 Fig. 10. This can be due to an overestimation of the radiative heat transfer from the walls of
 848 the wind tunnel that are assumed to behave as insulated black surfaces (no heat loss by
 849 radiation), which is surely not the case in Catchpole et al. experiments [12]. We cannot also
 850 exclude that, for rapid fires, the dimensions of the wind tunnel can affect very significantly
 851 some aspects of the fire dynamics that were more difficult to reproduce numerically.
 852 Paradoxically, even if the experimental conditions are well known at small scale in a
 853 laboratory, confined fires (especially for a very low fuel moisture content) can be more
 854 difficult to simulate numerically, because of the confinement effect resulting from the
 855 interactions between the fire and the walls of the wind-tunnel.

856

857 Consequently, the best results were obtained for relatively dense solid-fuel beds (the EXSC
 858 and MF series) with a solid-fuel volume fraction ranged between 0.009 and 0.018,
 859 compared to 0.005 for the other cases. It is also for these cases that the lowest values for
 860 the ROS (average and standard deviation) were obtained. Because a low value of the ROS
 861 means also a less intense fire (and consequently a smaller flame length), we can probably
 862 conclude that these differences of behavior observed between the considered set of
 863 numerical experiments could be imputed to the confinement effect induced by the walls of
 864 the wind-tunnel, which was less important in the case of most tests of the EXSC and MF
 865 series than in the case of EXMC series.

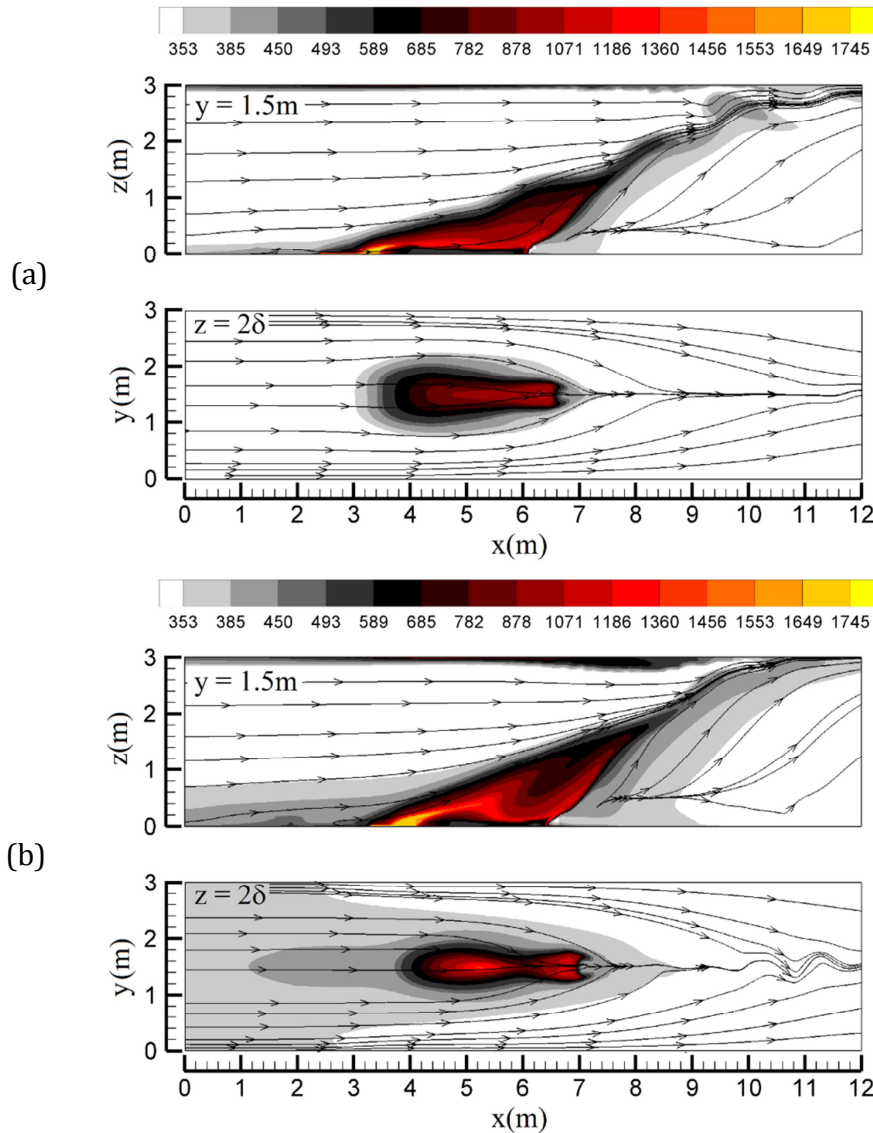
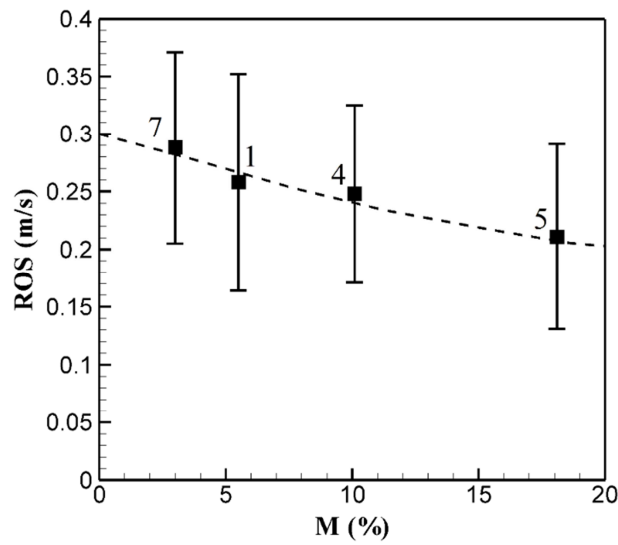


Fig. 11. Temperature fields and streamlines obtained numerically at $t = 45$ s (a) and at $t = 60$ s (b) in the case of experiment MF38 of Catchpole et al. [12] (heartwood sticks, wind speed of $U = 2.68$ m/s, moisture content $M = 6.2\%$, see Tab. 2 for more details). Top: solution in the vertical median plane ($y = 1.5$ m), bottom: solution in the horizontal plane at $z = 2\delta$.

866

867 To separately evaluate the dependence of the ROS on the fuel moisture content M , we have
 868 extracted four cases (EXMC23, EXMC36, EXMC48, EXMC69) for which all the simulation
 869 parameters were the same ($\alpha_s = 0.005$, $U = 2.68$ m/s, and $\delta = 0.203$ m), excepted the fuel
 870 moisture content M that varied between 3% and 18.1%. These results are shown in Fig. 12
 871 that clearly highlights the exponential decay of the ROS with the fuel moisture content; for
 872 comparison, an exponential curve $0.3 \times e^{-0.022M}$ (with M expressed in %) was represented on

873 the same Figure. This exponential decaying has been reported for the experimental data
 874 [12] but with an exponent equal to -0.0073 (nearly 3 times smaller than the value
 875 predicted by FireStar3D). We should note that the authors in [12] have indicated that this
 876 value also exhibited a standard error equal to 0.0035. In addition, it was not possible to
 877 obtained for these four cases a stabilized value of the rate of spread (the test bench being
 878 too short), which must be improve in the future.
 879



880 **Fig. 12.** Evolution of the rate of spread (ROS) as a function of the fuel moisture
 content (M) for fires propagating through regular excelsior. Experiment
 numbers are shown in Tab. 2 and in Tab. 3.

881
 882 This discrepancy in the exponent value between the simulations and the experiments could
 883 be explained by the fact that water loss from the vegetation was treated in the model as a
 884 simple evaporation process (a phase change at a fixed temperature) while the reality is
 885 more complex. The vegetation loses its water through a mechanism of evapotranspiration
 886 that starts at a temperature below 100°C. The characteristic time of an evapotranspiration
 887 process is longer than that of a pure evaporation process, and therefore it is not surprising
 888 than the impact of the fuel moisture content upon the rate of spread was more important in
 889 the model than in the reality.

890 5. Conclusions

892 A 3D physical model initially developed to predict wildfire behavior and referred to as
 893 FireStar3D has been described in this paper. The model consists of solving the conservation
 894 equations of the coupled system composed of the vegetation and the surrounding
 895 atmosphere, and takes into account the various physical phenomena encountered in a
 896 wildfire. Compared to other fire models, FireStar3D is based on a low Mach number

897 formulation and solves the transport and the reactive steps in the gaseous phase, which is
898 not the case for HIGRAD/FIRETEC [16]. The radiative heat transfer is fully predicted from
899 the resolution of the radiative transfer equation, which is not always the case in WFDS
900 where a filter is also applied with a presumed radiative fraction in some cases [17]. From a
901 numerical point of view, FireStar3D is based on an implicit solver, as it is the case in the
902 new generation of fire solvers such as FireFOAM [55,56]. A study was carried out in this
903 paper to evaluate the potential of FireStar3D to predict fire behavior in an
904 environmentally-controlled wind tunnel. This constitutes an important step toward the
905 validation of any physical model, in order to reach the final objective of numerically
906 simulating wildfire behavior at large scales. The results have shown that FireStar3D
907 predicted relatively well the correct order of magnitude of the ROS and the correct trends
908 induced by a variation of the wind speed and of the fuelbed characteristics (moisture
909 content and volume fraction), although it seems to overestimate the ROS, especially at low
910 packing ratios. The next step (work in progress) will be the numerical simulations of
911 surface fires in grasslands in similar conditions to those of the experiments carried in
912 Australia and in US [13–14]. With the new generation of outdoor experimental fires [14],
913 additional data can be compared, such as vertical velocity profiles and the time history of
914 the temperature and the turbulent kinetic energy monitored at different heights from the
915 ground. This new step will constitute a great progress in the validation process, because
916 the comparison will incorporate local data and not only integral ones such as the ROS and
917 the intensity of fire. Due to the complexity of the physical phenomena, we are conscious
918 that performing a real time forecast of a wildfire at a very large scale using this kind of
919 model might never be achieved. But this is not our objective; we consider however that this
920 class of physical model is well adapted to study the problem of the interaction between a
921 fire front and a building located at a wildland-urban interface. Other problems could be
922 studied with this kind of model such as the transition between plume-dominated and wind
923 driven fires (which constitutes the two major regimes of propagation of wildfires), the
924 impact of surface fire on soils, the interaction between two fire fronts, the behavior of fires
925 in extreme conditions (very dry fuel, strong wind, very high temperature conditions) which
926 could occur more frequently in the context of global warming, and many other questions in
927 connection with the understanding and the prevention of this natural hazard.

928

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- Numerical simulations of surface fire through an homogeneous fuel bed
- Detailed physical fire model
- Comparison with the experiments carried out in the wind-tunnel of the Missoula Fire Sciences Lab

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