



Simulations of flaming combustion and flaming-to-smoldering transition in wildland fire spread at flame scale

Mohamed Mohsen Ahmed ^{a,1}, Arnaud Trouvé ^{a,*}, Jason Forthofer ^b, Mark Finney ^b

^a Department of Fire Protection Engineering, University of Maryland, College Park, MD 20742, USA

^b USDA Forest Service, Missoula Fire Sciences Laboratory, Missoula, MT 59808, USA

ARTICLE INFO

Keywords:

Flame spread
Wildland fires
Pyrolysis
Char oxidation
Turbulent non-premixed combustion
Smoldering combustion

ABSTRACT

Our objective in the present study is to provide basic insights into the coupling between external-gas and solid biomass vegetation processes that control the dynamics of flame spread in wildland fire problems. We focus on a modeling approach that resolves processes occurring at vegetation and flame scales, *i.e.*, the formation of flammable vapors due to the thermal degradation of the solid biomass, the subsequent combustion in ambient air, the thermal feedback to the biomass through radiative and convective heat transfer, and the possible transition from flaming combustion (taking place outside of the solid biomass) to smoldering combustion (taking place inside the solid biomass). The capability uses a multiphase combustion framework and treats external-gas processes through a Large Eddy Simulation solver and solid biomass processes through a discrete particle model. The discrete particle model adopts a one-dimensional porous medium formulation, includes descriptions of drying, thermal pyrolysis, oxidative pyrolysis, and char oxidation, as well as a description of the external-gas-to-solid-biomass diffusion of oxygen mass; the discrete particle model thereby provides a treatment of in-depth oxidative processes and allows the simulation of smoldering combustion. The modeling capability is applied to the simulation of fire spread across a surrogate biomass vegetation bed corresponding to a discrete array of cylindrical-shaped, vertically-oriented, pine wood sticks, characterized by a monomodal size distribution, in horizontal flat terrain and under wind-aided conditions. The numerical results demonstrate that the model can simulate successful flaming-to-smoldering transition followed by complete biomass consumption.

Novelty and Significance statement:

- A new computational model is proposed to simulate wildland fire behavior at high levels of resolution capable of capturing vegetation- and flame-scale phenomena.
- Solid biomass vegetation processes are treated using a discrete particle model that features a porous medium formulation and includes a description of in-depth oxygen mass diffusion, and exothermic oxidative pyrolysis and char oxidation reactions.
- The computational model is shown to be capable of simulating the transition from flaming to smoldering combustion, often observed in wildland fire spread problems.

1. Introduction

Flame spread over solid fuel surfaces is a canonical problem in fire science relevant to both building and wildland fires. Building fires feature flames spreading along large continuous solid fuel surfaces, while wildland fires feature flames spreading over small disconnected solid fuel elements. Classical theory suggests that flame spread is controlled by several factors, including the thermal properties and possibly the thickness of the solid fuel material, the orientation of the exposed solid surfaces with respect to the vertical direction, and the velocity (magnitude and direction) of a possible external air flow [1,2]. Note

that classical flame spread theory primarily focuses on configurations with large flammable solids, *i.e.*, on the configurations relevant to building fires, and that not much is known on how to apply this theory to the configurations relevant to wildland fires. Previous experimental observations suggest that in the case of porous beds made of small dispersed flammable solid elements, flame spread is also controlled by a parameter that represents the solid-gas proportions inside the bed [3]; this parameter can be chosen as: the solid mass load, m'' , defined as the mass of solid elements per unit ground surface area; the packing ratio, β_s , defined as the volume fraction of solid inside the bed; or the separation distance, d , defined as the mean distance between the edges or the centers of adjacent solid elements.

* Corresponding author.

E-mail address: atrouve@umd.edu (A. Trouvé).

¹ Current affiliation: Materials Science Division, Lawrence Livermore National Laboratory.

Nomenclature**Abbreviations**

CFD	Computational Fluid Dynamics
EDM	Eddy Dissipation Model
FMC	Fuel Moisture Content
LES	Large Eddy Simulation
MLR	Mass Loss Rate
PBR	Particle Burning Rate
PIHF	Pseudo Incoming Heat Flux
ROS	Rate of Spread
RTE	Radiative Transfer Equation
TGA	Thermogravimetric Analysis

Symbols

β_s	fuel packing ratio
χ_{rad}	radiant fraction
ΔH	heat of combustion
Δ	spatial resolution
δ_{bed}	fuel bed height
$\dot{m}$	mass loss or production rate
$\dot{m}'''$	volumetric mass reaction rate
$\dot{m}''$	mass flux
$\dot{q}''$	heat flux
$\dot{Q}'$	fireline intensity
ϵ	emissivity
η	mass yield
μ	dynamic viscosity
Ω	radiation space solid angle
ρ	density
σ	Stefan–Boltzmann constant
Σ_p	particle surface-to-volume ratio
τ	residence time
c_p	specific heat at constant pressure
d	separation distance between fuel particles
d_p	fuel particle diameter
D_{flame}	flame horizontal base length
G	irradiation
g	gravitational acceleration
h	convective heat transfer coefficient
H_{flame}	vertical flame height
h_{mass}	convective mass transfer coefficient
I	directional radiation intensity
k	thermal conductivity
L_{flame}	flame length
m_s''	fuel load
N_C	Byram convection number
N_p	number of particles
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	temperature
t	time
u	velocity
V	volume
x	axial or streamwise coordinate
Y	mass fraction

y	elevation
z	lateral coordinate

Subscripts

∞	evaluated at the ambient
a	ash
bed	a control volume of solid vegetation and the gas-phase
c	char
ds	dry solid
g	gas
p	particle
Rco	char oxidation reaction
Rd	drying reaction
Rop	oxidative pyrolysis reaction
Rp	pyrolysis reaction
$surf$	evaluated at the particle surface
ws	wet solid

The topic of flame spread across discrete solid fuel elements has received significant attention in the fire science literature. Past work includes studies of flame spread across: discrete arrays consisting of engineered fuel elements (wooden sticks, paper strips, cardboard sticks, blocks of PMMA, etc) [4–24]; porous beds made of representative wildland surface biomass (pine needles, excelsior, etc) [25–28]; and full-scale plots of vegetation or representative clumps of real vegetation (shrublands, trees, etc) [29,30]. These past studies provide valuable information on the geometry and structure of the flame, the values of the rate of spread, the values of the fuel mass loss rate, and representative values of radiative and convective heat fluxes. This information is typically provided as a function of a fuel load parameter (m_s'' , β_s or d), an external air flow velocity, and/or an inclination angle of the ground surface.

Past studies also suggest that flames spreading across discrete fuels can be organized into two broad categories of combustion regimes. For instance, small-scale studies with laminar flames often belong to a “discrete combustion” regime in which the flame zone features multiple flames attached to individual fuel elements. In contrast, large-scale studies with turbulent flames generally belong to a “group combustion” regime in which the flame zone features a single envelope flame that covers multiple fuel elements. The transition between discrete and group combustion is not fully understood and is believed to be controlled by the level of ventilation of the flame zone [16,23].

Note that the mechanisms for flame spread in the discrete and group combustion regimes are likely to be quite different. For illustration, let us consider the case of horizontal arrays of vertical fuel elements in the presence of an external (horizontal) air flow. In the discrete combustion regime, the mechanics of concurrent (i.e., wind-aided) flame spread are often described as a repeated sequence of two steps: a first ignition step corresponding to convective heating up to an ignition temperature at the top of an adjacent fresh fuel element followed by a second downward propagation step corresponding to the spread of the newly ignited flame from top to bottom of the fuel element [4,5,8]. In contrast, in the group combustion regime, the mechanics of concurrent flame spread are often dominated by large coherent flow structures with complex interactions between externally-driven horizontal motions and buoyancy-driven vertical motions that result from Rayleigh–Taylor instabilities [12,13].

Furthermore, many studies report large variations in the dominant mode of heat transfer during flame spread: while laminar flame spread features a dominant contribution of convective heat transfer (often

described as “flame contact”) [4,5,8,27], turbulent flame spread features different regimes with a dominant contribution of radiative heat transfer in “plume-dominated” fires and a strong and possibly dominant contribution of convective heat transfer in “wind-driven” or “slope-driven” fires [17,29,30]. Recent work has shed some new light on the importance of convective heat transfer effects during flame spread under conditions aided by wind or slope [31,32]. Results in Refs. [31, 32] suggest in particular that these effects are size-dependent: while “large” fuel elements (*i.e.*, elements characterized by a thickness larger than 1 cm) feature moderate values of the convective heat transfer coefficient, $h \approx 10\text{--}20\text{ W/m}^2/\text{K}$, and are therefore only weakly sensitive to convective heating and cooling, “small” fuel elements (*i.e.*, elements characterized by a thickness smaller than 1 mm) feature higher values of the convective heat transfer coefficient, $h > 100\text{ W/m}^2/\text{K}$, and are found to be strongly sensitive to convective heating and cooling. The relative importance of the different modes of forward heat transfer is not fully understood and remains an open question in the literature on wildland fire dynamics.

Finally, while typically not the main focus of previous work, some of the past studies of flame spread across discrete solid fuel elements mention the presence of smoldering combustion after the passage of the flame front [13,17,23] with the associated possibility of complete degradation of the fuel elements into a solid residue made of ash, or incomplete degradation into a solid residue made of unreacted fuel and char [9]. Smoldering combustion is a key factor in wildland fires that often determines the overall impact of fires in terms of fuel consumption and gaseous emissions [3].

We now turn to a discussion of computational modeling of wildland fire spread. Following Verma et al. [33], we differentiate between: “multiphase combustion solvers” aimed at describing the coupling between pyrolysis, flow, combustion and radiation occurring at the vegetation and flame scales; “wildfire solvers” aimed at describing the coupling between combustion and flow occurring at fireline and/or geographical scales (*i.e.*, at characteristic scales of the terrain topography and land cover); and “atmospheric boundary layer solvers” aimed at describing the coupling between combustion and flow occurring at meteorological scales. We focus in the present study on the multiphase approach that provides a detailed description of wildland fire phenomena occurring at vegetation and flame scales, *i.e.*, from millimeter- to meter-scale. Multiphase combustion solvers typically resort to a classical Lagrangian–Eulerian framework in which continuum gas phase processes (mixing, combustion, convective heat transfer) are treated through a classical Computational Fluid Dynamics (CFD) Eulerian approach (nowadays a Large Eddy Simulation – LES – approach) while dispersed solid phase processes (drying, pyrolysis, char oxidation) are treated through a subgrid-scale, Lagrangian, discrete particle model [34–45]. Note that gas phase processes are simulated in three-dimensional space, while solid phase processes are simulated in either zero- or one-dimensional space (a zero-dimensional treatment assumes that the solid fuel elements are thermally- and compositionally-thin; a one-dimensional treatment considers that the solid fuel elements may become thermally- and compositionally-thick). Radiative heat transfer is simulated through the solution of a modified Radiative Transfer Equation (RTE) that accounts for the emission and absorption contributions of both gas and solid phases [46]. It is worth emphasizing that the multiphase combustion approach implicitly assume that the flames belong to the group combustion regime.

While past studies have successfully applied the multiphase combustion approach to simulations of wildland fire spread at flame scale [33–37,41–45], simulations to-date have been primarily focused on the description of flaming combustion with little or no attention paid to the topics of smoldering combustion and fuel consumption. Note that the description of smoldering combustion is considered challenging because early zero-dimensional models were limited by the assumption of char oxidation occurring at the surface of the solid fuel elements, an assumption that is not supported by current understanding and

experimental observations [47–49]. Simulation of smoldering combustion requires a suitable description of the transport of oxygen mass inside the particle and of the corresponding in-depth propagation of the char oxidation reactions from the surface to the core of the solid fuel elements. This type of description is now available in state-of-the-art models using a one-dimensional porous medium framework as proposed in Refs. [47,50].

Our general objective in the present study is to develop a computational modeling capability that simulates wildland fire behavior at vegetation and flame scales with detailed descriptions of thermal degradation processes occurring during both flaming and smoldering combustion. Our specific goal is to simulate flame spread across vegetation beds treated as a population of solid particles under prescribed topographic and wind conditions. We adopt the multiphase combustion framework and treat gas-phase processes through a LES solver based on a free, open-source, general-purpose, CFD library called OpenFOAM [51], and solid-phase processes through an in-house discrete particle solver based on the model developed by Lautenberger & Fernandez-Pello [47,50]. In the present simulations of flame spread, we focus on global fire behavior in terms of flame structure, fire intensity and particle mass loss rate, as well as on individual fuel particle responses as a function of the intensity and duration of the thermal loading process. Section 2 presents the physical models used in the multiphase approach. Section 3 presents the numerical configuration corresponding to a surrogate biomass vegetation bed. Section 4 presents results obtained in a simulation of the baseline configuration corresponding to a wind-aided flame spreading across a uniform horizontal bed made of 2-mm-diameter pine wood sticks. This simulation features sustained smoldering in the post-flame region and complete particle degradation. Conclusions are drawn in Section 5.

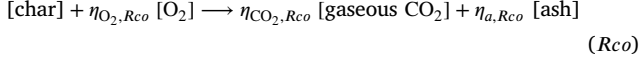
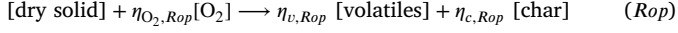
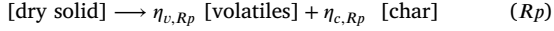
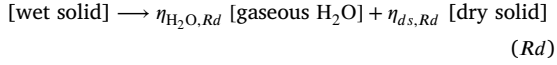
2. Physical models

As mentioned in the introduction section, we adopt the multiphase combustion approach [34–46] and treat the biomass vegetation bed as a population of cylindrical-shaped, vertically-oriented, fuel elements (also referred to as particles) of length δ_{bed} and diameter d_p . The choice of the number density and size of the particles determines the fuel load parameters (m'_s , β_s and d). Each particle is described in one-dimensional space as a porous medium with a (large) solid-phase and a (small) gas-phase, which allows for a detailed treatment of the particle-to-external-gas outflow of flammable mass and the external-gas-to-particle diffusion of oxygen mass; this detailed treatment is required to account for in-depth oxidative pyrolysis and char oxidation. We first present below the Particle Burning Rate (PBR) model used to describe in-particle processes (Section 2.1), including results from an intermediate calibration study performed at the micro- and bench-scales (see Appendix 2 in the supplementary material). We then briefly present the LES models used to describe external-gas processes (Section 2.2).

2.1. Particle burning rate (PBR) model

We follow previous work by Lautenberger & Fernandez-Pello [47] and describe each fuel particle as a matrix of pores featuring a solid-phase and a gas-phase. The composition of the solid-phase of the particle is described in terms of four constituents: wet solid (ws), dry solid (ds), char (c) and ash (a); the composition of the gas-phase is described in terms of oxygen O_2 . The fuel particles are made of pine wood. We consider that each particle may experience four heterogeneous (gas/solid) reactions: a drying reaction (R_d) that produces water vapor and dry solid; a thermal pyrolysis reaction (R_p) and an oxidative pyrolysis reaction (R_{op}) that produce gaseous fuel (called volatiles) for the external flaming combustion process as well as solid char; and

a char oxidation reaction (*Rco*) that produces combustion products (treated as carbon dioxide CO₂) and solid ash:



where $\eta_{\text{H}_2\text{O},Rd}$ and $\eta_{ds,Rd}$ are the mass yields of water vapor and dry solid in reaction (*Rd*), respectively, $\eta_{\text{H}_2\text{O},Rd} + \eta_{ds,Rd} = 1$; where $\eta_{v,Rp}$ and $\eta_{c,Rp}$ are the mass yields of volatiles and char in reaction (*Rp*), respectively, $\eta_{v,Rp} + \eta_{c,Rp} = 1$; where $\eta_{\text{O}_2,Rop}$ is the oxygen-to-dry-solid mass ratio, and $\eta_{v,Rop}$ and $\eta_{c,Rop}$ are the mass yields of volatiles and char in reaction (*Rop*), respectively, $\eta_{v,Rop} + \eta_{c,Rop} = 1 + \eta_{\text{O}_2,Rop}$; and where $\eta_{\text{CO}_2,Rco}$ is the oxygen-to-char mass ratio, and $\eta_{\text{CO}_2,Rco}$ and $\eta_{a,Rco}$ are the mass yields of carbon dioxide and ash in reaction (*Rco*), respectively, $\eta_{\text{CO}_2,Rco} + \eta_{a,Rco} = 1 + \eta_{\text{O}_2,Rco}$. Reactions (*Rd*) and (*Rp*) require high enough temperatures and are endothermic; in contrast, reactions (*Rop*) and (*Rco*) require both high enough temperatures and the presence of oxygen, and are exothermic.

Note that we treat the initial biomass composition as “wet solid” and do not represent its cellulose, hemicellulose and lignin components, as is often done in current wood pyrolysis models [52]; because of the difficulties found in the coupling of the PBR and LES models (see below), we prefer using the simpler modeling approach of Ref. [47]; this choice may be re-visited in future work. Furthermore, in the present PBR model, we do not differentiate between the char products of the thermal and oxidative pyrolysis reactions (*Rp*) and (*Rop*). We also do not differentiate between the gaseous products of reactions (*Rp*) and (*Rop*) and describe instead these products as a single lumped chemical species called volatiles (*i.e.*, fuel for gaseous combustion). In addition, we focus here on the heterogeneous reactions that produce fuel for flaming combustion and implicitly assume that this fuel will burn externally, *i.e.*, outside of the particles. Hence, possible homogeneous (gas/gas) reactions that may take place between volatiles and oxygen inside the particle pores are ignored. Finally, we treat the gaseous products of reaction (*Rco*) as carbon dioxide and ignore the possible presence of products of incomplete combustion.

We follow the modeling choices made in Refs. [47,50] and characterize each solid-phase constituent (*us*, *ds*, *c* and *a*) by a set of reference values for the thermal properties (mass density, heat conductivity, heat capacity, surface emissivity) and for the porous medium parameters (porosity, permeability) (see Appendix 1 in the supplementary material); these reference values correspond to a limiting state in which the particle is made of one solid-phase constituent only. The heat conductivity and heat capacity are treated as functions of temperature, and radiation across pores is described as an effective heat conductivity [47]. We also characterize each reaction ((*Rd*), (*Rp*), (*Rop*) and (*Rco*)) by a set of values for the chemical kinetics parameters (pre-exponential factor, activation energy, solid-phase reactant and gas-phase oxygen exponents), for the stoichiometric coefficients and for the heats of reactions (see Appendix 1 in the supplementary material). For the most part, the values of the model coefficients presented in Appendix 1 are taken directly from Ref. [47] where these values are determined by calibration against experimental data obtained in (bench-scale) cone calorimeter experiments. We make two exceptions to using the input data of Ref. [47]. A first exception is that the values of the chemical kinetics parameters for reactions (*Rp*), (*Rop*) and (*Rco*) are taken from Ref. [53] where these values are determined by calibration against experimental data obtained in (micro-scale) thermogravimetric analysis experiments; we found that this choice provides a better representation of the two validation data sets available at micro- and bench-scales (see Appendix 2 in the supplementary material). A

second exception is the introduction of a submodel to describe the variations of the thermal properties of the wet solid, *us*, with the particle moisture content, $FM C = \eta_{\text{H}_2\text{O},Rd} / (1 - \eta_{\text{H}_2\text{O},Rd})$; these variations are taken from Ref. [54].

While the Particle Burning Rate (PBR) model developed in the present work can accommodate changes in particle volume, we follow Ref. [47] and treat each thermal degradation reaction, (*Rd*), (*Rp*), (*Rop*) and (*Rco*), as an iso-volumetric process (a questionable approximation that will be re-visited in future work). Furthermore, in-particle flow is treated as pressure-driven through the classical Darcy's law. The model also assumes thermal equilibrium between the solid and gas phases and both phases are treated with the same temperature.

In summary, the PBR model solves for four solid species mass equations (*us*, *ds*, *c* and *a*), one temperature equation, one gaseous oxygen mass equation and one pressure equation (Appendix 1 in the supplementary material). We solve the PBR equations using classical first- and second-order spatial discretization techniques (a “mesh-based model” in the review of solution methods presented in Ref. [55]) and a one-dimensional formulation that can accommodate rectangular-, cylindrical- or spherical-shaped geometries [50,56]; the present study considers cylindrical-shaped particles. The PBR equations are integrated in time using an implicit (iterative) approach that treats convection and diffusion through a second-order, Crank–Nicolson method and chemical reaction through a first-order, backward Euler method. The computational mesh is spatially-uniform and the PBR solver features a re-meshing capability (that is unused in the present study because the particles have constant volume). The PBR solver also features an adaptive time resolution algorithm that controls the value of the time step to guarantee small incremental variations in the simulated particle temperature (typically no more than 0.1 K during each update of the solution). The PBR solver was initially developed in MATLAB and then translated to C++ for integration into OpenFOAM.

The coupling between the internal solid-gas processes described by the PBR model and the external gas-phase processes taking place outside of the particle occurs through boundary conditions written at the particle surface. These boundary conditions account for mass, momentum and energy transfer. We refer the reader to a detailed presentation in Appendix 1 in the supplementary material and limit our discussion below to the external-gas-to-particle heat flux and oxygen mass flux, noted $\dot{q}''_{g \rightarrow p}$ and $\dot{m}''_{\text{O}_2, g \rightarrow p}$ respectively. $\dot{q}''_{g \rightarrow p}$ describes the heating or cooling of the particle surface due to convective and radiative heat transfer; we write:

$$\dot{q}''_{g \rightarrow p} = h \times (T_{g,\infty} - T_{p,surf}) + \epsilon_{p,surf} \times (G - \sigma T_{p,surf}^4) \quad (1)$$

where h is the convective heat transfer coefficient (in units of W/m²/K), $T_{g,\infty}$ the temperature of the ambient gas surrounding the particle (in units of K), $T_{p,surf}$ the temperature of the particle surface (in units of K), $\epsilon_{p,surf}$ the (non-dimensional) emissivity of the particle surface, G the incoming radiative heat flux (in units of W/m²) and σ the Stefan–Boltzmann constant (in units of W/m²/K⁴). $T_{g,\infty}$ and G are input quantities to the PBR model; in a typical PBR calculation, these quantities are either user-specified or are obtained from the CFD solution that calculates external gas-phase quantities. Note that in a CFD calculation, G can be directly evaluated from the integral of the directional radiation intensities I over (4π) -steradian angular space, $G = (\int_{4\pi} I d\Omega)/4$, with I obtained from the solution of the Radiative Transfer Equation. The convective heat transfer coefficient h is a function of the magnitude of the external flow velocity $u_{g,\infty}$ (and also of $T_{g,\infty}$, see below) and should therefore also be viewed as an input quantity to the PBR model.

Furthermore, $\dot{m}''_{\text{O}_2, g \rightarrow p}$ describes the oxygen transport to the particle surface due to convective and diffusive mass transfer; we write:

$$\dot{m}''_{\text{O}_2, g \rightarrow p} = h_{mass} \times (Y_{g,\text{O}_2,\infty} - Y_{g,\text{O}_2,surf}) \quad (2)$$

where h_{mass} is the convective mass transfer coefficient (in units of kg/s/m²), $Y_{g,\text{O}_2,\infty}$ the mass fraction of oxygen in the ambient gas surrounding the particle, and $Y_{g,\text{O}_2,surf}$ the mass fraction of oxygen at

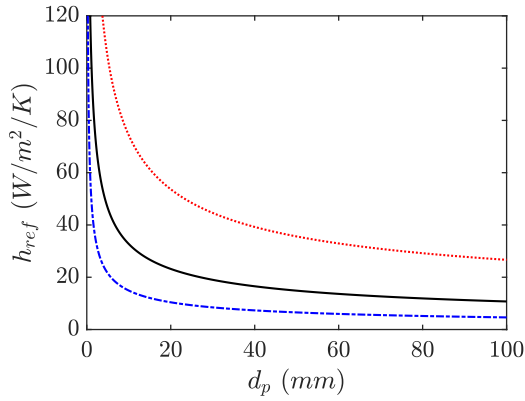


Fig. 1. Variation of the convective heat transfer coefficient, h_{ref} , with the particle diameter, d_p , as predicted by Eqs. (4)–(5). Case with air at normal temperature and pressure conditions and flowing at a velocity $u_{g,\infty} = 0.2$ (dashed-dotted line), 1 (solid line) or 5 m/s (dotted line).

the particle surface. $Y_{g,O_2,\infty}$ is an input quantity to the PBR model; in a typical PBR calculation, this quantity is either user-specified or is obtained from the CFD solution that calculates external gas-phase quantities. Also, using standard arguments, we assume an analogy between heat and mass transfer, relate h_{mass} to h , and write $h_{mass} = (h/c_{p,g})$, where $c_{p,g}$ is the heat capacity of the gas (in units of J/kg/K) in the boundary layer surrounding the particle and is evaluated at the film temperature, $T_{film} = (T_{g,\infty} + T_{p,surf})/2$ [57].

Thus, in the expressions of $\dot{q}_{g \rightarrow p}''$ and $\dot{m}_{O_2,g \rightarrow p}''$, the contributions of convective heat and mass transfer rely on the description of the convective heat transfer coefficient h . In Ref. [47], h is described as a baseline reference value, $h_{ref} = 10 \text{ W/m}^2/\text{K}$, modified by blowing effects:

$$h = \frac{\dot{m}_{p \rightarrow g}'' \times c_{p,g}}{\exp(\dot{m}_{p \rightarrow g}'' \times c_{p,g}/h_{ref}) - 1} \quad (3)$$

where $\dot{m}_{p \rightarrow g}''$ is the mass flow rate of gases at the particle surface (in units of kg/s/m²), which is an output quantity of the PBR model (at steady state, this quantity is equal to the particle mass loss rate). Note that the expression in Eq. (3) predicts that $h \approx h_{ref}$ when the intensity of the blowing is low, $\dot{m}_{p \rightarrow g}'' \approx 0$. The expression also predicts decreasing values of h when the intensity of the blowing increases; this prediction is consistent with the well-known heat protection effect provided by transpiration.

In the present study, we modify this model in order to better represent particle size effects previously reported in Refs. [31,32]. The modification consists in treating h_{ref} through standard, Nusselt-number-based, engineering correlations:

$$h_{ref} = \text{Nu}_{d_p} \times \frac{k_g}{d_p} \quad (4)$$

where Nu_{d_p} is the Nusselt number of the particle (based on the particle diameter), and k_g the heat conductivity of the gas (in units of W/m/K) evaluated at the film temperature. The Nusselt number is obtained from one of the recommended correlations found in the heat transfer literature [58]:

$$\text{Nu}_{d_p} = 0.3 + \frac{0.62 \times \text{Re}_{d_p}^{0.5} \times \text{Pr}^{1/3}}{(1 + (\frac{0.4}{\text{Pr}})^{2/3})^{1/4}} (1 + (\frac{\text{Re}_{d_p}}{282000})^{5/8}) \quad (5)$$

where Re_{d_p} is the Reynolds number of the particle, $\text{Re}_{d_p} = (\rho_g u_{g,\infty} d_p)/\mu_g$, with ρ_g and μ_g the mass density and dynamic viscosity of the gas (in units of kg/m³ and Pa-s, respectively), and where Pr is the Prandtl number, all properties being evaluated at the film temperature.

Note that the expressions in Eqs. (4) and (5) predict that h goes to infinity when the particle diameter d_p goes to 0 (see Fig. 1). This

prediction is qualitatively consistent with the experimentally-observed increase in the sensitivity of particles to the effects of convective heating and cooling as the thickness of the particles is reduced [31,32].

Appendix 2 in the supplementary material presents a discussion of the results obtained in an intermediate evaluation of the performance of the PBR model through comparisons with experimental data taken from (micro-scale) thermo-gravimetric analysis (TGA) experiments and (bench-scale) cone calorimeter experiments. These comparisons confirm in particular that the PBR model is capable of reproducing the dramatic increase in MLR observed when going from anaerobic to air conditions. This increase in MLR is explained by a direct contribution of the oxidative reactions, (*Rop*) and (*Rco*), to MLR, as well as by an indirect contribution through heat release, higher temperatures and a corresponding increase in the rate of the thermal pyrolysis reaction, (*Rp*).

2.2. Large Eddy Simulation (LES) models

The gas-phase solver used in the present study is a software package based on a free, open-source, general-purpose, CFD library called OpenFOAM [51]. OpenFOAM offers the option of a low-Mach-number LES model that uses second-order accurate, finite volume discretization techniques with implicit time integration; the solver features advanced meshing capabilities (structured or unstructured polyhedral mesh); it also features a massively parallel computing capability using Message Passing Interface (MPI) protocols.

OpenFOAM provides a choice between several modeling options for the treatment of turbulence, combustion and thermal radiation. In the present study, subgrid-scale turbulence is described using the Wall-Adapting Local Eddy-viscosity (WALE) model [59]; combustion is described using the classical concept of a global combustion equation combined with the Eddy Dissipation Model (EDM) [60]; radiation is described by solving the Radiative Transfer Equation (RTE) using a discrete-ordinates, finite-volume method [61] and by assuming a non-scattering grey medium and using the concept of a prescribed global radiant fraction, $\chi_{rad} = 0.35$. These models are standard in fire modeling and are briefly presented in Appendix 1 in the supplementary material. In the global combustion equation, we assume that the fuel composition (i.e., the composition of the gaseous volatiles produced by thermal and oxidative pyrolysis reactions) is $\text{C}_{3.4}\text{H}_{6.2}\text{O}_{2.5}$ [62]; the heat of combustion is specified as $\Delta H_{flaming} = 15.6 \text{ MJ/kg}$.

In addition to the heat and oxygen mass exchanges discussed in the previous section, the main quantity of interest in coupled particle-gas processes is the particle mass loss rate, $\dot{m}_{p \rightarrow g}$, and more specifically the fuel mass loss rate, $\dot{m}_{fuel,p \rightarrow g}$. These quantities are outputs of the PBR model:

$$\dot{m}_{p \rightarrow g} = \int_{V_p} ((1 - \eta_{ds,Rd}) \times \dot{m}_{Rd}''') dV_p + \dot{m}_{fuel,p \rightarrow g} + \int_{V_p} ((1 - \eta_{c,Rco}) \times \dot{m}_{Rco}''') dV_p \quad (6)$$

and

$$\dot{m}_{fuel,p \rightarrow g} = \int_{V_p} ((1 - \eta_{c,Rp}) \times \dot{m}_{Rp}''') + (1 - \eta_{c,Rop}) \times \dot{m}_{Rop}''' dV_p \quad (7)$$

where $\dot{m}_{Rk}'''$ designates the volumetric mass reaction rate of reaction (*Rk*) and where integration takes place across the volume of the particle.

3. Numerical configuration

The surrogate biomass vegetation bed considered in the present study is an array of discrete, cylindrical-shaped, vertically-oriented, elongated fuel elements. The baseline configuration corresponds to a uniform array made of identical fuel particles of length δ_{bed} , diameter d_p , (initial) mass density ρ_p , and (initial) moisture content *FMC* (see Table 1). We choose $d_p = 2 \text{ mm}$ and the particle surface-to-volume ratio is $\Sigma_p = (4/d_p) = 2000 \text{ m}^{-1}$. The packing ratio is $\beta_s = 0.005$. The bulk

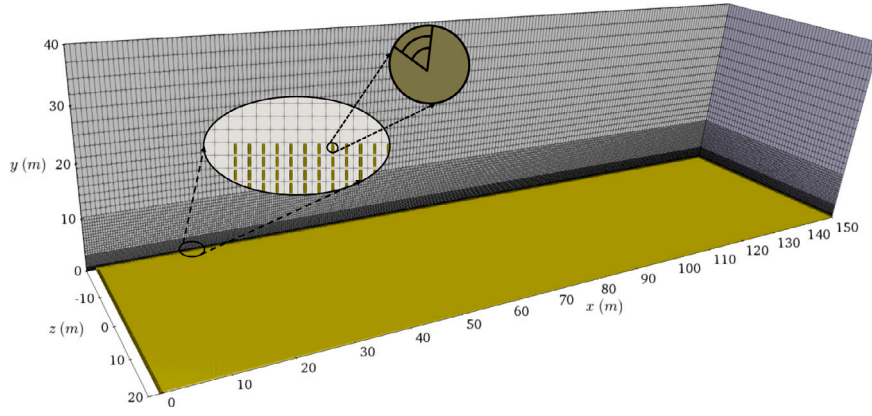


Fig. 2. Computational domain corresponding to a surrogate biomass vegetation bed located on flat ground and treated as an array of subgrid-scale discrete particles. The computational mesh is structured and features four different blocks with different levels of spatial resolution along the vertical direction.

Table 1

Parameters of the baseline surrogate biomass vegetation bed.

Parameter	Symbol	Value/Initial value
Vertical bed height (m)	δ_{bed}	0.4
Particle diameter (mm)	d_p	2
Surface-to-volume ratio (m^{-1})	Σ_p	2000
Particle mass density (kg/m^3)	ρ_p	380
Particle moisture content (-)	FMC	0.053
Packing ratio (-)	β_s	0.005
Bulk mass density (kg/m^3)	$\rho_{s,bulk}$	1.9
Solid mass load (kg/m^2)	m''_s	0.76

mass density, defined as the mass of solid particles per unit volume of the solid-gas bed, is then $\rho_{s,bulk} = (\rho_p \times \beta_s) = (380 \times 0.005) = 1.9 \text{ kg/m}^3$; and the solid mass load is $m''_s = (\rho_{s,bulk} \times \delta_{bed}) = (1.9 \times 0.4) = 0.76 \text{ kg/m}^2$. The horizontal distance that separates the centers of adjacent particles is $d = ((\pi d_p^2/4)/\beta_s)^{0.5} \approx 25 \text{ mm}$.

Note that the biomass contains non-flammable material and that only a fraction of the available solid biomass can turn into fuel for combustion. For instance, in the description of thermal degradation offered by the present PBR model (Section 2.1), a fraction, $\eta_{H_2O,Rd} = (1 - \eta_{ds,Rd})$, of the initial mass m''_s will evaporate as water vapor and the remaining fraction, $\eta_{ds,Rd}$, will become dry solid. Assuming that a fraction, α , of that dry solid will evolve through the pyrolysis reaction (Rp) and the remaining fraction, $(1 - \alpha)$, will evolve through the pyrolysis reaction (Rop), the yield of volatiles produced by the two parallel reactions is $(\alpha \times (1 - \eta_{c,Rp}) + (1 - \alpha) \times (1 - \eta_{c,Rop}))$; since in the present model $\eta_{c,Rp} = \eta_{c,Rop}$, the yield simplifies to $(1 - \eta_{c,Rp})$, and the maximum value of the mass of volatiles per unit ground surface area is then $m''_{volatiles} = (\eta_{ds,Rd} \times (1 - \eta_{c,Rp}) \times m''_s) \approx (0.95 \times (1 - 0.202) \times 0.76) = 0.576 \text{ kg/m}^2$. These volatiles are the fuel for the external gaseous combustion process. Similarly, the yield of char produced by the two parallel reactions (Rp) and (Rop) is $(\alpha \times \eta_{c,Rp} + (1 - \alpha) \times \eta_{c,Rop})$, which simplifies here to $\eta_{c,Rp}$, and the maximum value of the mass of char per unit ground surface area is $m''_{char} = (\eta_{ds,Rd} \times \eta_{c,Rp} \times m''_s) \approx (0.95 \times 0.202 \times 0.76) = 0.146 \text{ kg/m}^2$. This char is the fuel for the in-particle char oxidation process.

The ground surface of the fuel bed is assumed flat and horizontal. The bed is exposed to strong horizontal wind conditions characterized by a power-law profile for the mean velocity, $u_{wind} = u_{ref} \times (y/y_{ref})^{(1/7)}$, where u_{ref} is a reference value of the wind velocity, $u_{ref} = 5 \text{ m/s}$, taken at a reference vertical elevation $y = y_{ref} = 2 \text{ m}$. Turbulence-like fluctuations are superposed on the mean inflow velocity profile using temporal sinusoidal oscillations and an assumed 10% fluctuation intensity. The wind direction is assumed to be constant.

The computational domain is 152-m long in the streamwise (wind) x -direction, $(-2) \leq x \leq 150 \text{ m}$, 40-m wide in the spanwise (cross-wind)

z -direction, $(-20) \leq z \leq 20 \text{ m}$, and 40-m high in the vertical (ground-normal) y -direction, $0 \leq y \leq 40 \text{ m}$ (Fig. 2). The ground surface of the computational domain ($y = 0$) is flat and horizontal, and is treated with a no-slip adiabatic condition (the no-slip and adiabatic boundary conditions are convenient but questionable approximations that will be re-visited in future work and that are believed to have insignificant impact in the present study). The fuel bed starts at $x = -0.5 \text{ m}$ and extends to $x = 150 \text{ m}$, which was determined to be long enough to achieve steadily-propagating fire conditions. Periodic boundary conditions are applied at the lateral planes, $z = \pm 20 \text{ m}$, with the intent to simulate an infinite line fire with two-dimensional statistics. The west boundary ($x = -2 \text{ m}$) is an inflow boundary with prescribed wind flow velocity. The top and the east boundaries ($y = 40 \text{ m}$ and $x = 150 \text{ m}$) are treated as open inflow/outflow boundaries (velocity and pressure boundary conditions dynamically adapt according to the normal direction of the flow). Hydrostatic effects are accounted for at these boundaries by applying the *prghTotalHydrostaticPressure* option available in the OpenFOAM library, with a reference height and pressure at the top boundary equal to 40 m and 10864.3 Pa, respectively. The pressure gradient at the east and west boundaries is dynamically adjusted based on the flow direction; the pressure gradient at the west boundary is also dynamically adjusted based on the prescribed velocity; the pressure gradient at the ground surface is zero. Line ignition is achieved by using a slot burner located on the ground surface at $(-0.5) \leq x \leq 0 \text{ m}$ and $(-20) \leq z \leq 20 \text{ m}$, and releasing gaseous fuel at 0.01 m/s and 1600 K for a duration of 10 s. The high temperature of the slot burner fuel is artificial; it is used to increase radiant heating and to guarantee successful rapid ignition of the adjacent wood sticks. The ignition heat release rate per unit spanwise length is $\sim 52 \text{ kW/m}$.

The computational mesh is block-structured and the computational domain is decomposed into three refinement regions and a far field region. The mesh in region 1, $0 \leq y \leq 0.8 \text{ m}$, features cubic cells of 10-cm size; the mesh in region 2, $0.8 \leq y \leq 3 \text{ m}$, features cubic cells of 20-cm size; the mesh in region 3, $3 \leq y \leq 10 \text{ m}$, features cubic cells of 40-cm size; and the mesh in the far field region, $10 \leq y \leq 40 \text{ m}$, features 80-cm resolution in the x - and z -directions and a stretched grid in the vertical y -direction. The fuel bed is located in region 1 and most of flaming combustion occurs in regions 1 and 2. The mesh features a total of 7,362,500 computational cells. The fuel bed occupies a total volume equal to $(150.5 \times 40 \times 0.4) = 2408 \text{ m}^3$; with 10-cm spatial resolution, the total number of grid cells inside the bed region is 2,408,000. Because the fuel bed features fuel elements with a single size, we assign 1 subgrid-scale computational particle to each cell inside the bed region (additional computational particles would be needed in the case of a size distribution); the total number of computational particles is therefore 2,408,000. Note that in this

framework, a computational particle represents N_p fuel elements, with $N_p = \beta_s \times \Delta_1^2 / (\pi d_p^2 / 4)$, where Δ_1 is the spatial resolution in region 1; we have $N_p = 0.005 \times (0.1)^2 / (\pi (0.002)^2 / 4) \approx 16$ (1 computational particle represents 16 physical fuel elements). Note also that each fuel element has a vertical height $\delta_{bed} = 0.4$ m, and is split and assigned to 4 vertical bed cells.

Other numerical choices are as follows. The baseline resolution used in the PBR model for an individual pine wood particle is $\Delta x_s = 25$ μ m. This relatively high resolution was found to be necessary to avoid numerical instability problems and to accurately capture the stiff spatial variations associated with the char oxidation reaction (in the PBR model, the thickness of the char oxidation reaction can be as low as 0.1 mm, see Fig. 11(c) below). Appendix 3 in the supplementary material presents a discussion of the suitability of the spatial resolution choices for Δ_1 and Δx_s .

The number of radiation angles used in the decomposition of angular space used by the RTE solver is 144. The time-step of the LES solver is controlled using a classical Courant–Friedrichs–Lewy (CFL) condition and is on the order of 0.004 s (4 ms). The time step of the radiation RTE solver is 10 times larger or 0.04 s. The time-step of the PBR solver is controlled by in-particle temperature variations (Section 2.1) and varies between 0.2 and 4 ms. These short values of the PBR time step are occasionally required to capture thermal runaway phenomena associated with the start of the exothermic char oxidation reaction.

The simulations are performed using 200 processors and Message Passing Interface protocols on a distributed-memory parallel-computing cluster. In the baseline configuration, the simulation of 60 s of fire spread requires approximately 25,000 CPU hours. The baseline simulation runs for close to 300 s and therefore corresponds to a total CPU cost of approximately 125 kCPU hours.

4. Results obtained in the baseline configuration

We first present below results that characterize the mean flame structure and global fire behavior (Section 4.1). We then present results that characterize the exposure and response of individual fuel particles inside the surrogate biomass vegetation bed (Section 4.2).

4.1. Global flame structure

Results indicate that the simulated flame spreads across the fuel bed at a quasi-constant rate into the x -direction of the wind. The flame features a spatially distorted front with strong cross-wind z -variations (see Figs. 3(a) and 3(b)). These z -variations correspond to an oscillatory flame pattern that is similar to the peak-and-trough structure reported in Ref. [13]. This peak-and-trough flame structure results from interactions between wind-driven horizontal motions and buoyancy-driven vertical motions that are generated by Rayleigh–Taylor instabilities [13]. Results also reveal the presence of a large smoldering combustion region behind the leading flaming combustion region: in Figs. 3(a) and 3(b), the flaming region is visualized by high gas temperatures above the fuel bed, while the smoldering region is visualized by high particle temperatures inside the fuel bed. These results indicate that the present LES-PBR model is capable of describing flaming-to-smoldering transition.

Fig. 4 presents the time variations of the position of the foremost and rearmost points of the flame, pyrolysis and smoldering regions. The flame region is defined as the region where the gas-phase volumetric heat release rate, quantified by the EDM model, is greater than a threshold value of 1 kW/m³. The pyrolysis region is defined as the region where the fuel mass loss rate, $\dot{m}_{fuel,p \rightarrow g}''$, quantified by the PBR model, is greater than a threshold value of 1 g/m²/s. The smoldering region is defined as the region where $\dot{m}_{fuel,p \rightarrow g}'' < 1$ g/m²/s and the heat release rate inside the particles is positive. Fig. 4 shows that after time $t \approx 50$ s, the variations in position have become quasi-linear and the different curves are approximately parallel, which suggests that the

spread rate of the fire is constant and that the statistical flame structure has reached a steady state (note that Fig. 5 suggests that steady state is not achieved until $t > 100$ s, see below). The rate of spread of the flame, noted ROS , can then be calculated as the slope of the variations displayed in Fig. 4. We find $ROS \approx 0.37$ m/s. This simulated value is in good agreement with (i.e., within 15% of) the predicted value given by the classical Rothermel model [63]; we find $ROS_{Rothermel} \approx 0.33$ m/s.

Fig. 5 presents the corresponding time variations of the heat release rate intensity, defined as the heat release rate per unit spanwise length. In the present fire spread problem, the heat release process has two components: a first homogeneous (gas-gas) component that takes place outside of the pine wood particles, fueled by volatiles produced by the thermal and oxidative pyrolysis reactions, and corresponding to flaming combustion; and a second heterogeneous (solid-gas) component that takes place inside of the pine wood particles, fueled by dry solid and char, and corresponding to smoldering combustion. As already mentioned, in the present LES-PBR solver, the first flaming combustion component is treated by the EDM model while the second smoldering combustion component is treated by the PBR model through the (exothermic) oxidative reactions, (Rop) and (Rco). Fig. 5 shows that after time $t \approx 100$ s, i.e., after an initial transient overshoot, these variations become quasi-constant and lead to the following estimates: $\dot{Q}'_{flaming} \approx 3.3$ MW/m and $\dot{Q}'_{smoldering} \approx 1.8$ MW/m. Thus, the total fireline intensity is approximately 5.1 MW/m and flaming (smoldering) heat release represents 65% (35%) of the total.

Note that these results are consistent with estimates of the fuel load presented above. In Section 3, we calculated that $m''_{volatiles} \approx 0.576$ kg/m² and $m''_{char} \approx 0.146$ kg/m². Let us first consider flaming combustion. Using Byram's classical expression that relates fireline intensity to rate of spread and fuel load [3], one can write: $\dot{Q}'_{flaming} = m''_{volatiles} \times ROS \times \Delta H_{flaming} \approx 0.576 \times 0.37 \times 15.6 \approx 3.3$ MW/m, which is in excellent agreement with EDM-based results. Note that this calculation assumes complete gaseous fuel consumption (i.e., complete transformation of volatiles into carbon dioxide and water vapor), an assumption that is satisfied in the present fire spread problem.

Let us now consider smoldering combustion. Simulations suggest that the weight of oxidative pyrolysis reactions (Rop) in the (in-particle) heat release process is much smaller than that of char oxidation reactions (Rco). Under those conditions, we can write: $\dot{Q}'_{smoldering} \approx m''_{char} \times ROS \times \Delta H_{Rco}$, where ΔH_{Rco} is the heat of the (Rco) reaction (see Appendix 1 in the supplementary material); we then calculate $\dot{Q}'_{smoldering} \approx 0.146 \times 0.37 \times 37.7 \approx 2.0$ MW/m, which is close to (within 10% of) PBR-based results. Note that this calculation assumes complete particle consumption (i.e., complete transformation of wet solid into ash), an assumption that is almost satisfied in the baseline configuration (it is found that in PBR simulations, burnout typically occurs with a small amount of unreacted char left at the core of the particles).

We now turn to a brief discussion of the fire regime. The estimates of the values of ROS and $\dot{Q}'_{flaming}$ allow calculating the Byram convection number, N_C , which provides a metric to differentiate between “wind-driven” and “plume-dominated” fires [33]. We have: $N_C = (2 \times \dot{Q}'_{flaming} \times g) / ((\rho_{\infty} c_{p,\infty} T_{\infty}) \times (u_{wind,ref} - ROS)^3)$, where g is the gravitational acceleration, ρ_{∞} , $c_{p,\infty}$ and T_{∞} the mass density, heat capacity (at constant pressure), and temperature of ambient air, respectively, and $u_{wind,ref}$ the magnitude of the wind velocity at mid-flame height (we use $u_{wind,ref} \approx u_{ref}$). We then calculate: $N_C \approx (2 \times (3.3 \times 10^6) \times 9.8) / ((1.2 \times 1000 \times 293) \times (5 - 0.37)^3) \approx 1.8$. This low value of the Byram convection number, $N_C < 2$, suggests that the simulated flame is at, or close to conditions that are representative of the “wind-driven” fire regime.

Furthermore, the simulated flame clearly belongs to the group combustion regime with characteristic length scales for the flaming and smoldering combustion regions that are large compared to the separation distance between discrete fuel elements. We provide here an estimate of these length scales. The mean flame geometry can be described as an inclined triangle and can be therefore characterized by

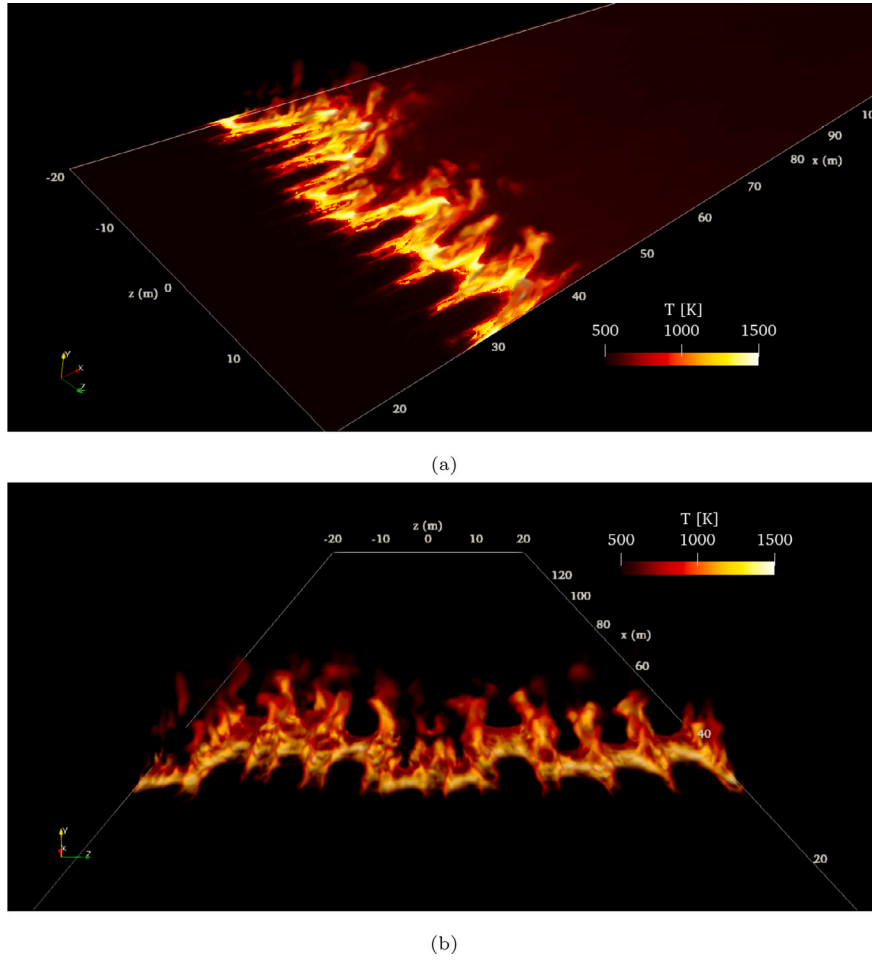


Fig. 3. Instantaneous snapshot of high-temperature iso-contours ($T > 550$ K) used to visualize both the flaming and smoldering regions of the fire. (a) Perspective view (the fire spreads from lower-left to upper-right) in which gases and solid particles are colored by temperature; (b) Rear view (the fire spreads from front to rear) in which gases are colored by temperature and solid particles are not represented.

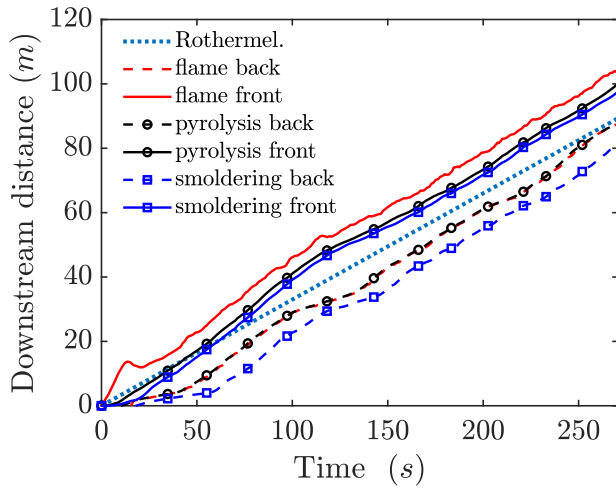


Fig. 4. Time evolution of the x -positions of the front and back edges of the flame, pyrolysis and smoldering regions. The dotted line correspond to predictions based on the Rothermel model.

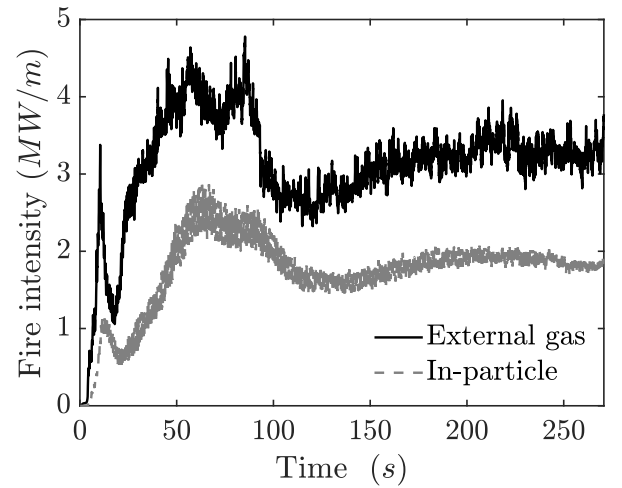


Fig. 5. Time evolution of the heat release rate intensity due to external flaming combustion (black solid line) and to in-particle smoldering combustion (gray dashed line).

a vertical height, H_{flame} , and an horizontal base length called depth, D_{flame} ; we find $H_{flame} \approx 5.6$ m and $D_{flame} \approx 1.5$ m. It is interesting to compare these results to available correlations for flame height of linefires in the absence of wind. Using a first correlation due to

Byram [64], one finds: $L_{flame} = 0.0775 \times (\dot{Q}'_{flaming}/1000)^{0.46} \approx 0.0775 \times (3300)^{0.46} \approx 3.2$ m; using a second correlation due to Yuan & Cox [65], one finds $L_{flame} = 0.034 \times (\dot{Q}'_{flaming}/1000)^{2/3} \approx 0.034 \times (3300)^{2/3} \approx 7.5$ m;

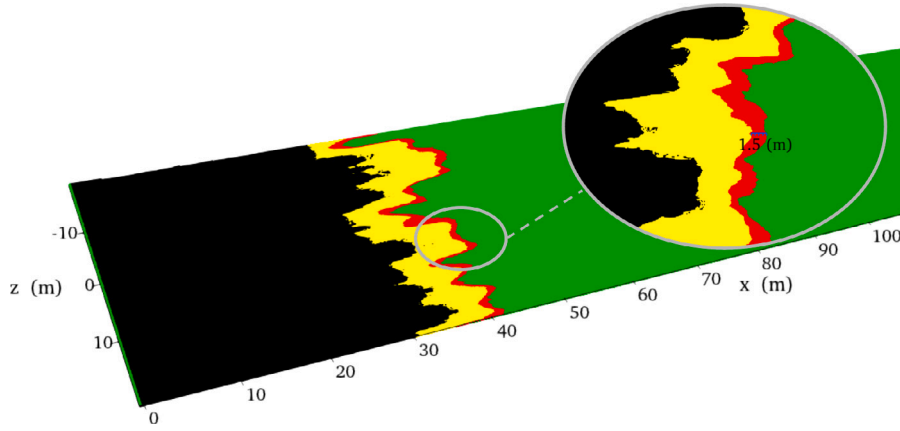


Fig. 6. Instantaneous snapshot showing the burning state of the particles inside the fuel bed. Unburnt particles are colored in green; particles inside the pyrolysis region are colored in red; particles inside the smoldering region are colored in yellow; burnt particles are colored in black. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

using another, more recent correlation due to Finney & Grumstrup [66], one finds $L_{flame} = 0.01051 \times (\dot{Q}'_{flaming}/1000)^{0.774} / (D_{flame})^{0.161} \approx 0.01051 \times (3300)^{0.774} / (1.5)^{0.161} \approx 5.2$ m. While not directly relevant to the present wind-driven conditions, these estimates confirm that the flame length is on the order of several meters.

Fig. 6 presents a different perspective and focuses on the burning state of particles inside the fuel bed. The color coding differentiates between unburnt particles made of wet or dry solid, particles inside the pyrolysis region that produce fuel for flaming combustion, particles inside the smoldering region that undergo char oxidation, and burnt particles made of ash. The pyrolysis and smoldering regions feature strong z -oscillations that are similar to those already observed in the flame in Figs. 3(a) and 3(b). This suggests that the peak-and-trough flame structure is associated with strong variations in the rate of thermal degradation of the solid fuel. While beyond the scope of the present study, future work should investigate the apparent correlations between the z -variations of the flame, the external-gas-to-particle thermal feedback and the particles mass loss rate.

Fig. 6 allows a quantification of the mean thickness of the pyrolysis and smoldering regions: we find $D_{pyrolysis} \approx D_{flame} \approx 1.5$ m and $D_{smoldering} \approx 9.5$ m. This suggests that the average residence time associated with pyrolysis reactions is approximately $\tau_{pyrolysis} = (D_{pyrolysis}/ROS) \approx (1.5/0.37) \approx 4$ s. Similarly, the average residence time associated with smoldering reactions is approximately $\tau_{smoldering} = (D_{smoldering}/ROS) \approx (9.5/0.37) \approx 26$ s. If one considers that during $\tau_{smoldering}$, the char oxidation reaction taking place inside each fuel particle travels from the surface to the center of the particle, one finds the following estimate for the propagation speed of the char oxidation front: $S_{smoldering} \approx ((d_p/2)/\tau_{smoldering}) \approx (10^{-3})/26 = 3.8 \times 10^{-5}$ m/s, or 2.3 mm/min.

4.2. Particles exposure and response

We now consider the viewpoint of individual fuel particles with the objective to characterize the exposure and the response of these particles due to the passing fire. Fig. 7 presents representative time variations of relevant environmental conditions at a given location inside the fuel bed chosen at mid-bed height, at $(x, y, z) = (40, 0.2, 0)$ m. It is found that: gas temperatures, $T_{g,\infty}$, inside the fuel bed reach peak values close to 1200 K (note that these values correspond to LES filtered quantities and that peak flame temperatures remain unresolved in the simulation and may be expected to be higher than 1200 K); flow velocities, $u_{g,\infty}$, reach peak values close to 2 m/s (note that these values are significantly lower than u_{ref} due to the lower elevation and to drag effects inside the fuel bed); the irradiation, G , reach peak values as high as 180 kW/m²; and the mass fraction of oxygen, $Y_{g,O_2,\infty}$,

decreases to 0. Each plotted quantity features significant fluctuations; these fluctuations are the consequence of buoyancy-driven instabilities and turbulent flow behavior.

Furthermore, Fig. 7(a) shows that starting at $t = 40$ s, $T_{g,\infty}$ first increases slowly from ambient value to approximately 450 K, and then increases rapidly around $t \approx 117$ s. The rapid increase at $t \approx 117$ s can be interpreted as the flame/plume arrival time. This interpretation is confirmed by examining Fig. 7(d), where values of $Y_{g,O_2,\infty}$ close to 0 are observed between approximately $t \approx 120$ and 130 s. In the classical description of the structure of diffusion flames, the region with no or little oxygen corresponds to the fuel-side region of the flame (also called the underfire region) and the 10-s period with little oxygen in Fig. 7(d) can be interpreted as the flame residence time. Thus, results in Fig. 7 suggest that $t \approx 117$ s is the hot plume arrival time, $t \approx 120$ s is the flame arrival time, and $t \approx 130$ s is the flame departure time. These estimates are different from, but are consistent with our previous calculation of the average residence time associated with pyrolysis reactions, $\tau_{pyrolysis} \approx 4$ s; the discrepancies can be explained by differences between monitoring quantities related to in-particle pyrolysis and quantities related to external flaming, and also by statistical variations along the fire zone (see the discussion of Fig. 10(d) below), and we can conclude that the flame passage time is on the order of 5–10 s. Finally, Fig. 7(c) shows that the irradiation remains small prior to the flame/plume arrival time, i.e. prior to $t < 117$ s, a result that suggests that in the present configuration which features a small radiation penetration length ($\delta_{rad,s} = 0.4$ m), radiant emissions only contribute to flame spread at short distances.

Fig. 8 presents the corresponding time variations of the heat flux experienced by the fuel particle located at $(x, y, z) = (40, 0.2, 0)$ m. Fig. 8(a) presents the variations of the total external-gas-to-particle heat flux, $\dot{q}''_{g \rightarrow p}$, while Figs. 8(b) and 8(c) present the variations of the convective and radiative components of the total heat flux, $\dot{q}''_{conv} = h \times (T_{g,\infty} - T_{p,surf})$ and $\dot{q}''_{rad} = \epsilon_{p,surf} \times (G - \sigma T_{p,surf}^4)$, respectively. It is found that all heat flux quantities are strongly time-dependent and evolve from initially positive values (that indicate heating of the particle by its surroundings) to negative values (that indicate cooling). This evolution is explained by the combined effects of external heating and in-particle exothermic reactions: in the initial phase dominated by external heating, as the particle surface temperature, $T_{p,surf}$, increases from its initial ambient value to values that are several 100s K above ambient, the net heat flux takes reduced values due to the decreasing difference in temperature between the particle and its surroundings; in a subsequent phase, dominated by in-particle exothermic (char oxidation) reactions, as the particle surface temperature, $T_{p,surf}$, reaches values above 1200 K, the external heat transfer changes sign from a heating mode to a cooling mode. Thus, we find that the net heat

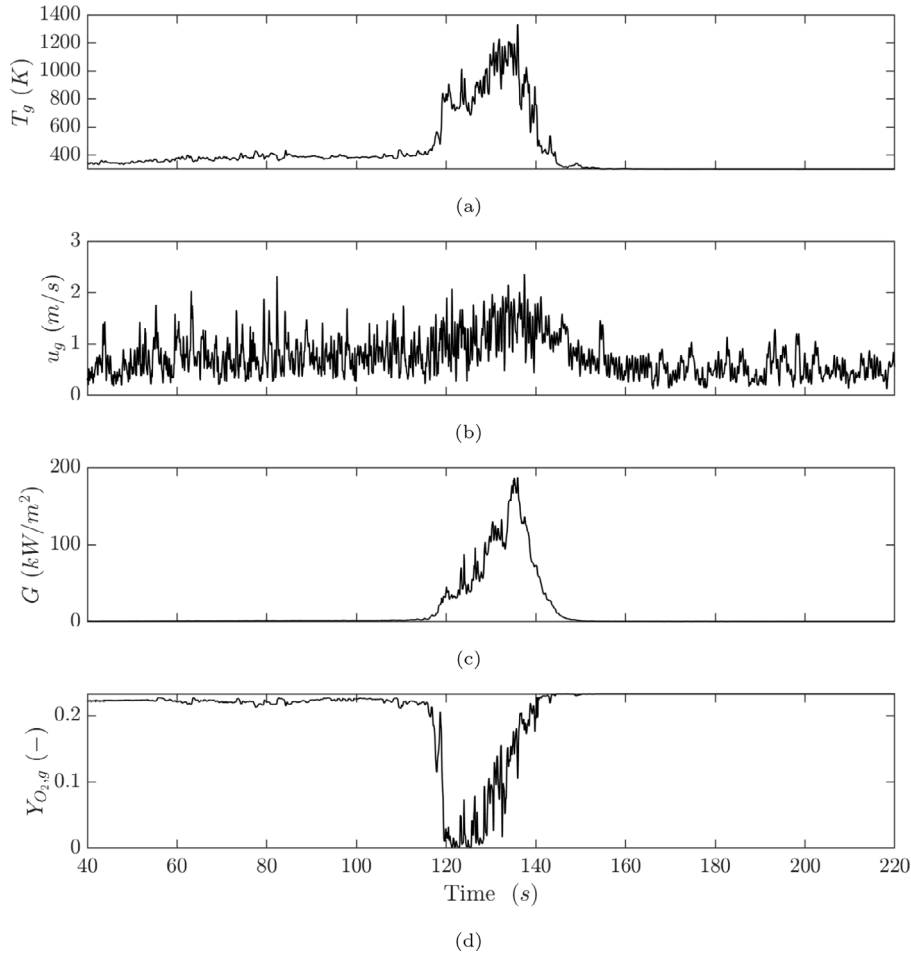


Fig. 7. Time evolution of characteristic environmental conditions experienced by a given particle located inside the vegetation bed at $(x, y, z) = (40, 0.2, 0)$ m: (a) gas temperature, $T_{g,\infty}$; (b) magnitude of gas velocity, $u_{g,\infty}$; (c) incoming radiation heat flux (irradiation), G ; (d) oxygen mass fraction, $Y_{g,O_2,\infty}$.

flux, $\dot{q}''_{g \rightarrow p}$, as well as its convective and radiative components, are quantities that are difficult to interpret because of their strong temporal variations, and also because these quantities combine information on external thermal loading parameters, *i.e.*, $T_{g,\infty}$ and G , with information on the particle response, *i.e.*, $T_{p,surf}$. In other words, $\dot{q}''_{g \rightarrow p}$, $\dot{q}''_{conv}$ and $\dot{q}''_{rad}$ are not convenient metrics to characterize the exposure of the fuel particles.

To characterize the exposure of the fuel particles, we propose using a new variable called the “pseudo incoming heat flux”, noted PIHF, and defined as the part of the net heat flux that depends on external parameters and does not depend on the particle response:

$$\text{PIHF} = h \times T_{g,\infty} + \epsilon_{p,surf} \times G \quad (8)$$

We have by construction: $\text{PIHF} = \dot{q}''_{g \rightarrow p} + (h \times T_{p,surf} + \epsilon_{p,surf} \times \sigma T_{p,surf}^4)$. Note that the convective heat transfer coefficient, h , is not rigorously independent of the particle response since it depends on $T_{p,surf}$ through the boundary layer film temperature; this dependence is weak, however, and we accept the implicit simplification.

In the following, we note PIHF_0 the reference ambient value of PIHF, $\text{PIHF}_0 = (h \times T_{g,0} + \epsilon_{p,surf} \times \sigma T_{g,0}^4)$, where $T_{g,0}$ is the ambient air temperature. The quantity $(\text{PIHF} - \text{PIHF}_0)$, called excess PIHF, is positive and can now be conveniently used to quantify the external heat loading due to the passing fire. We can also decompose the pseudo incoming heat flux into a convective component, noted PIHF_{conv} , and a radiative component, noted PIHF_{rad} ; we get:

$$(\text{PIHF}_{conv} - \text{PIHF}_{conv,0}) = h \times (T_{g,\infty} - T_{g,0}) \quad (9)$$

and

$$(\text{PIHF}_{rad} - \text{PIHF}_{rad,0}) = \epsilon_{p,surf} \times (G - \sigma T_{g,0}^4) \quad (10)$$

These quantities provide a convenient quantification of the weights of convective and radiative heat transfer without being obscured by the particle response. Note that the concept that leads to PIHF is similar to that of an “adiabatic surface temperature” (AST) occasionally used in heat transfer applications, *e.g.*, in film cooling applications and in problems of fire-structure interactions [67]. An important difference between PIHF and AST is that PIHF measures the intensity of the external thermal load in units of a heat flux (rather than a temperature).

Fig. 9(a) presents the time evolution of the excess pseudo incoming heat flux, $(\text{PIHF} - \text{PIHF}_0)$. It is seen that for $40 \leq t \leq 117$ s, excess PIHF takes small values which correspond to the slow preheating phase already identified in Fig. 7(a). Between times $t \approx 117$ and 146 s, excess PIHF takes large values, with peak values above 250 kW/m², which correspond to the intense heating phase associated with both flaming and smoldering combustion. The duration of this intense heating phase (defined as the duration when $(\text{PIHF} - \text{PIHF}_0)$ is greater than 10% of its peak value) is approximately 26 s.

Fig. 9(b) presents the corresponding variations of the convective and radiative components of excess PIHF. These results demonstrate that in the present configuration, the thermal loading of fuel particles corresponds to a mixed mode of heat transfer with comparable weights of convection and radiation. More precisely, calculations of integrated values indicate that during the intense heating phase, the contribution of convective (radiative) heat transfer is 47% (53%) of the total averaged value of excess PIHF (calculated to be 101 kW/m²).

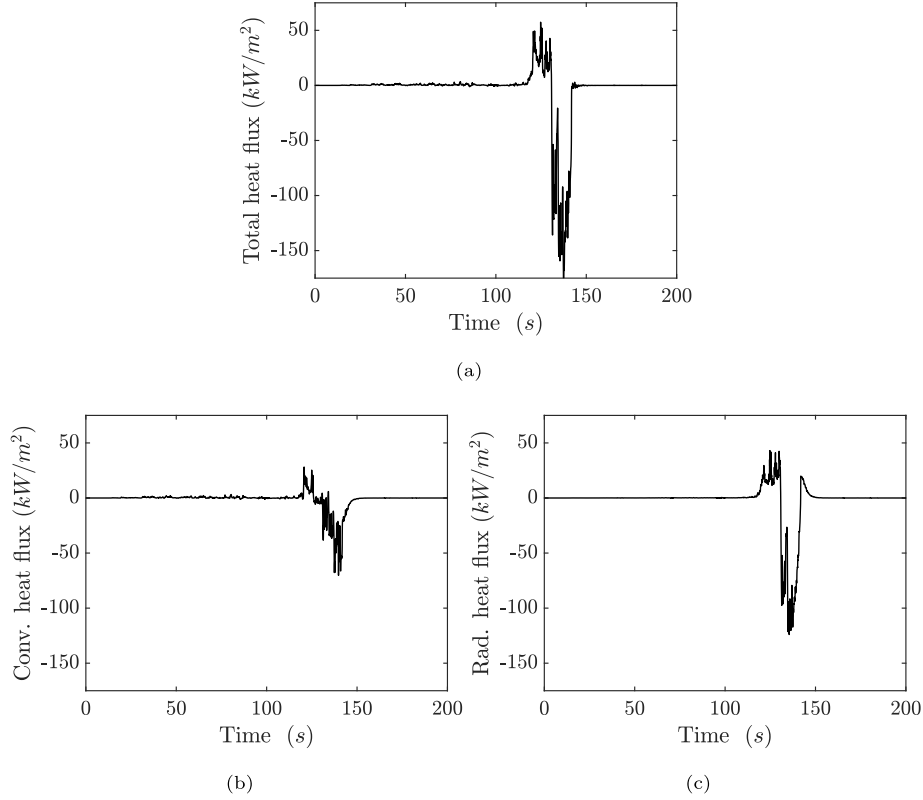


Fig. 8. Time evolution of the thermal load conditions experienced by a given particle located inside the vegetation bed at $(x, y, z) = (40, 0.2, 0)$ m: (a) total heat flux, $\dot{q}_{g \rightarrow p}''$; (b) convective heat flux, $\dot{q}_{conv}''$; (c) radiative heat flux, $\dot{q}_{rad}''$.

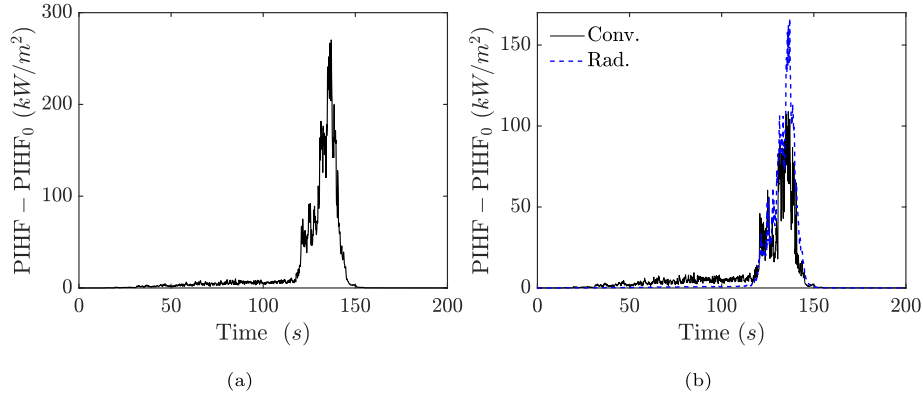


Fig. 9. Time evolution of the excess “pseudo incoming heat flux” experienced by a given particle located inside the vegetation bed at $(x, y, z) = (40, 0.2, 0)$ m: (a) total incoming heat flux, $(PIHF - PIHF_0)$; (b) convective and radiative components, $(PIHF_{conv} - PIHF_{conv,0})$ and $(PIHF_{rad} - PIHF_{rad,0})$.

We now turn to a discussion of the response of the particle subjected to the environmental conditions and thermal exposure already characterized in Figs. 7 and 9. Fig. 10(a) presents the time variations of the surface and core temperatures of the particle. The results confirm that for $30 \leq t \leq 117$ s, the particle undergoes a slow preheating phase with temperatures increasing to approximately 400 K, and for $117 \leq t \leq 146$ s, an intense heating phase with temperatures reaching values as high as 1500 K. Note that these high values are consistent with the smoldering combustion temperatures reported in Ref. [68], which range from 700 to 1200 degrees Celsius. The similar values taken by the surface and core temperatures demonstrate that the solid particle is thermally thin. Fig. 10(b) presents the corresponding variations of the composition of the solid phase of the particle as it evolves from wet to dry solid, from dry solid to char, and finally from char to ash. Note that

the mass quantities are normalized by the initial mass of the particle. Fig. 10(b) shows that: the preheating phase, $t \leq 117$ s, corresponds to slow drying of the particle; the evaporation of the particle moisture accelerates at time $t \approx 120$ s and is rapidly followed by pyrolysis and char oxidation reactions. Figs. 10(c) and 10(d) present the corresponding variations of the mass loss rate and of the different contributions to MLR due to reactions (R_d), (R_p), (R_{op}) and (R_{co}) (see Eq. (6)). The MLR quantities are normalized by the initial mass of the particle. Oscillations in MLR observed in Figs. 10(c) and 10(d) may be explained by the strong fluctuations in ambient oxygen mass observed in Fig. 7(d). Fig. 10(d) shows that: the thermal degradation of the particle consists in three successive steps, drying, pyrolysis and char oxidation, and this with little overlap (the present particle is thin); pyrolysis takes place between $t \approx 125$ and 131 s; thermal pyrolysis dominates over oxidative

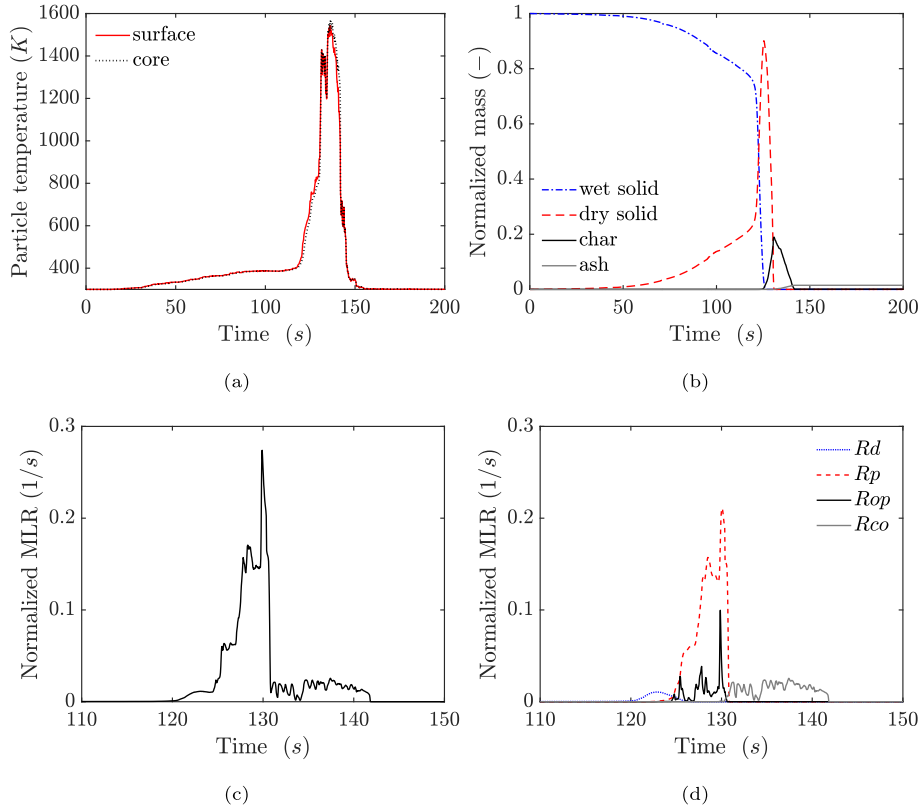


Fig. 10. Time evolution of the response of the particle located inside the vegetation bed at $(x, y, z) = (40, 0.2, 0)$ m: (a) particle surface and core temperatures; (b) normalized mass of solid-phase constituents (ws , ds , c , and a); (c) normalized MLR; (d) contributions of reactions (Rd), (Rp), (Rop) and (Rco) to normalized MLR.

pyrolysis; and char oxidation takes place between $t \approx 131$ and 146 s (there is a sudden drop in the rate of char oxidation at $t \approx 142$ s; this drop is followed by a phase characterized by low positive values of $\dot{m}''_{Rco}$ until burnout at $t \approx 146$ s). Based on the previously introduced definitions, the duration of pyrolysis ($\dot{m}''_{fuel,p \rightarrow g} > 1$ g/m²/s) is $\tau_{pyrolysis} = 6$ s and the duration of smoldering ($\dot{m}''_{fuel,p \rightarrow g} < 1$ g/m²/s and positive in-particle heat release rate) is $\tau_{smoldering} = 15$ s. These estimates are different from, but are consistent with our previous calculations of an average pyrolysis time of 4 s and an average smoldering time of 26 s; the discrepancies can be explained by statistical variations along the flame (see for instance the z -variations in the thickness of the pyrolysis and smoldering regions observed in Fig. 6). We can conclude that the duration of pyrolysis is on the order of 5 s and the duration of smoldering on the order of 15–35 s.

The global transformations presented in Fig. 10 are the net result of spatial variations occurring in the depth of the particle. Fig. 11 focuses on these spatial variations and presents instantaneous profiles of the volume fractions X_k , defined as the bulk volume occupied by the solid species k ($k = ws, ds, c$, or a) per unit bulk volume of the particle (see Appendix 1 in the supplementary material). Fig. 11(a) presents the instantaneous profile of X_{ws} and X_{ds} at a representative time $t = 121.3$ s taken during the drying phase of the particle. One can observe that the wet and dry solid coexist across the entire particle, and that the spatial variations in X_{ws} and X_{ds} remain small (less than a factor 2); these results indicate that the drying reaction (Rd) is distributed across the volume of the particle and that the particle can be considered as compositionally thin. Fig. 11(b) presents similar results for X_{ds} and X_c at a representative time $t = 127.8$ s taken during the pyrolysis phase of the particle. One can observe that the dry solid and char coexist across the entire particle, and that the variations in X_{ds} and X_c have limited amplitude (less than a factor 3); these results indicate that the pyrolysis reactions (Rp) and (Rop) are distributed across the

volume of the particle and that the particle can be considered as close to compositionally thin.

Finally, Fig. 11(c) presents similar results and focuses on the instantaneous profile of X_c and X_a at a representative time $t = 138$ s taken during the char oxidation phase of the particle. One can now observe a dramatically different picture: char and ash do not coexist across the particle except for a thin region (of approximately 0.1 mm thickness) that separates a pure char zone ($X_c = 1$ and $X_a = 0$) located on the core side of the particle and a pure ash zone ($X_c = 0$ and $X_a = 1$) located on the side of the exposed surface; these results indicate that the char oxidation reaction (Rco) has a thin front topology and that the particle is compositionally thick. During smoldering combustion, the char oxidation front propagates from the surface to the core of the particle at a velocity on the order of a few mm/min. Fig. 11(c) also plots the spatial variations of the mass fraction of gaseous oxygen $Y_{O_2,g}$. It is seen that: at the particular selected time ($t = 138$ s) the value of $Y_{g,O_2,surf}$ is close to 0.09 and that $Y_{O_2,g}$ varies linearly from $Y_{g,O_2,surf}$ at the particle surface to 0 at the location of the char oxidation front; there is no oxygen near the core of the particle. These variations are typical of a reaction that is limited by external-gas-to-particle oxygen diffusion (a result that is consistent with the high particle temperatures displayed in Fig. 10(a) since high temperatures promote fast chemistry and diffusion-controlled reaction). Note that the stiff variations observed in Fig. 11(c) justify the choice of a high resolution made for the PBR grid, $\Delta x_s = 25$ μ m.

5. Conclusion

This study presents a new computational modeling capability aimed at simulating wildland fire behavior at high-resolution. The capability uses a multiphase combustion framework and treats external-gas processes through a LES solver based on OpenFOAM [51], and in-particle solid-gas processes through a discrete particle burning rate

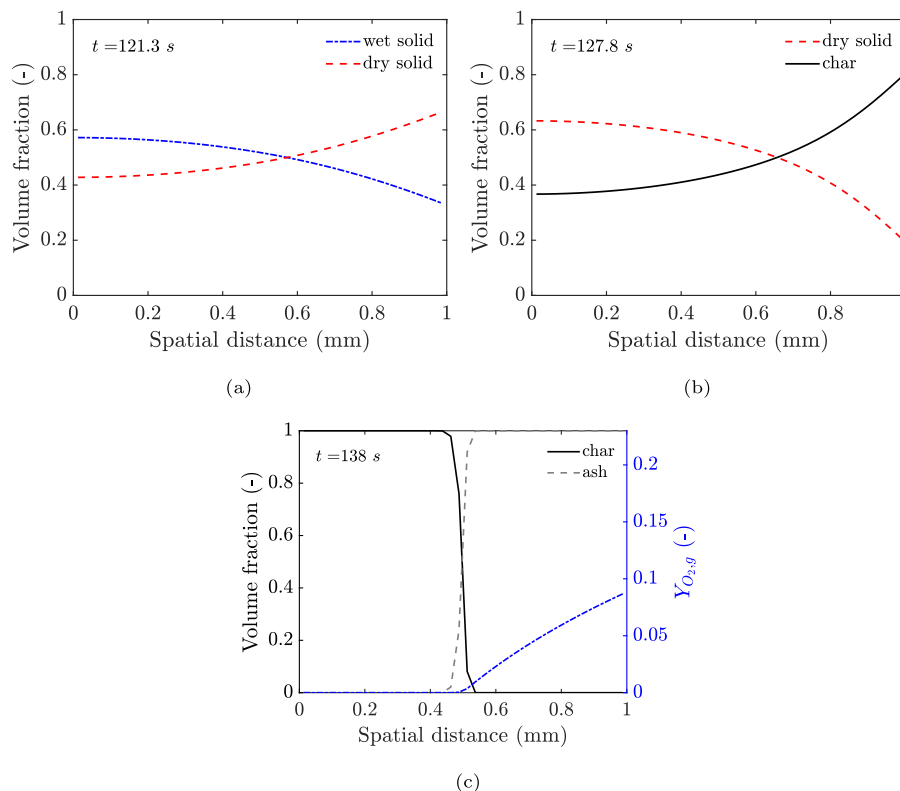


Fig. 11. Instantaneous snapshots of the spatial variations of the composition of the solid mass inside the particle located in the vegetation bed at $(x, y, z) = (40, 0.2, 0)$ m: (a); volume fractions of wet and dry solid at time $t = 121.3$ s; (b) volume fractions of dry solid and char at time $t = 127.8$ s; and (c) volume fractions of char and ash at time $t = 138$ s. The core (exposed surface) of the particle is on the left (right) of each plot. Fig. 11(c) also includes the instantaneous profile of the mass fraction of gaseous oxygen $Y_{O_{2,g}}$.

(PBR) model, based on a formulation originally proposed by Lautenberger & Fernandez-Pello [47,50]. The PBR model adopts a one-dimensional porous medium formulation, includes descriptions of drying, thermal pyrolysis, oxidative pyrolysis, and char oxidation, as well as a description of the external-gas-to-particle diffusion of oxygen mass; the PBR model thereby provides a treatment of in-depth oxidative processes and allows the simulation of smoldering combustion. The PBR model is a subgrid-scale model in the LES framework.

The LES-PBR model is applied to the simulation of fire spread across a surrogate biomass vegetation bed corresponding to a discrete array of cylindrical-shaped, vertically-oriented, pine wood sticks, in horizontal flat terrain and under wind-aided conditions. The simulation uses sub-millimeter-scale spatial resolution in the PBR biomass solver and centimeter-scale spatial resolution in the gas phase LES solver and thereby resolves the exchanges of mass, momentum and heat associated with pyrolysis, combustion, radiation and flow at flame and vegetation scales. In the baseline configuration, the sticks have a diameter of 2 mm and the simulated fire spread features “wind-driven” propagation, a two-zone structure with a leading flaming combustion zone followed by a trailing smoldering combustion zone, a rate-of-spread of 0.37 m/s, a fireline intensity of 5.1 MW/m, with a 65%/35% split between flaming and smoldering combustion, oxygen-diffusion-controlled char oxidation, and complete particle degradation (*i.e.*, complete transformation of the pine wood into ash). These results demonstrate that the LES-PBR model can simulate flaming-to-smoldering transition.

To characterize the thermal exposure of individual biomass particles, we first consider traditional diagnostics based on the net surface heat flux and based on its convective and radiative heat transfer components. It is found that these diagnostics are strongly time-dependent and are difficult to interpret because they contain information on both the external thermal load and the particle response. We then introduce a new variable called the “pseudo incoming heat flux” (PIHF) defined

as the part of the net surface heat flux that depends on external heat parameters (the local irradiation and the gas temperature) but does not depend on the particle response. The PIHF is shown to be a convenient diagnostic to characterize the intensity and duration of the thermal exposure, as well as to quantify the relative weights of convective and radiative heat transfer in fire spread processes. In the baseline configuration, it is found that convective and radiative heat transfer have approximately equal weights (47% vs. 53%).

While the present work is informed by experimental data since the PBR model is calibrated against experimental data obtained in micro-scale (thermo-gravimetric analysis) and bench-scale (cone calorimeter) pine wood experiments, while also the present simulations provide a value of the rate-of-spread that is in good agreement (within 15%) with predictions from the classical Rothermel model, and while the simulations produce many results that seem to be in qualitative agreement with experimental observations, we recognize that the present study does not establish the quantitative capability of the LES-PBR model and that further validation studies are needed. Validation studies are ongoing and will be reported in future publications.

Ongoing work is also aimed at establishing the ability of the present LES-PBR model to simulate both complete and incomplete consumption of solid biomass particles, *i.e.* the ability to simulate not only thin particles that are completely consumed but also thick particles that are only partially consumed by a passing fire.

CRediT authorship contribution statement

Mohamed Mohsen Ahmed: Developed software, Performed simulations, Analyzed data, Wrote the paper. **Arnaud Trouvé:** Designed research plan, Supervised work, Developed software, Analyzed data, Wrote the paper. **Jason Forthofer:** Advised on research plan, Reviewed results, Reviewed the paper. **Mark Finney:** Advised on research plan, Reviewed results, Reviewed the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This project is financially supported by the USDA Forest Service, Missoula Fire Sciences Laboratory, USA. The project is also supported by supercomputing resources made available by the University of Maryland, USA (<https://www.glue.umd.edu/hpcc/>) and by the US National Science Foundation (ACCESS Program, Grant number TG-CTS140046, <https://access-ci.org>). Parts of this manuscript were prepared under the auspices of the US DOE by Lawrence Livermore National Laboratory, USA under Contract DE-AC52-07NA27344.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.combustflame.2024.113370>.

References

- [1] D. Drysdale, *An Introduction to Fire Dynamics*, third ed., Wiley, 2011.
- [2] J.G. Quintiere, *Fundamentals of Fire Phenomena*, Wiley, 2006.
- [3] M.A. Finney, S.S. McAllister, T.P. Grumstrup, J.M. Forthofer, *Wildland Fire Behavior - Dynamics, Principles and Processes*, CSIRO Publishing, 2021.
- [4] M. Vogel, F.A. Williams, Flame propagation along matchstick arrays, *Combust. Sci. Technol.* 1 (1970) 429–436.
- [5] R.O. Weber, A model for fire propagation in arrays, *Math. Comput. Modelling* 13 (1990) 95–102.
- [6] G.F. Carrier, F.E. Fendell, M.F. Wolff, Wind-aided firespread across arrays of discrete fuel elements. I. Theory, *Combust. Sci. Technol.* 75 (1991) 31–51.
- [7] M.F. Wolff, G.F. Carrier, F.E. Fendell, Wind-aided firespread across arrays of discrete fuel elements. II. experiment, *Combust. Sci. Technol.* 77 (1991) 261–289.
- [8] T. Beer, Fire propagation in vertical stick arrays: the effects of wind, *Int. J. Wildland Fire* 5 (1995) 43–49.
- [9] J. Lozano, W. Tachajapong, H. Pan, A. Swanson, C. Kelley, M. Princevac, S. Mahalingam, Experimental investigation of the velocity field in a controlled wind-aided propagating fire using particle image velocimetry, in: *Fire Saf. Sci., Proceedings of the 9th International Symposium*, 2008, pp. 255–266.
- [10] M.J. Gollner, Y. Xie, M. Lee, Y. Nakamura, A.S. Rangwala, Burning behavior of vertical matchstick arrays, *Combust. Sci. Technol.* 184 (2012) 585–607.
- [11] J. Park, J. Brucker, R. Seballos, B. Kwon, Y.-T.T. Liao, Concurrent flame spread over discrete thin fuels, *Combust. Flame* 191 (2018) 116–125.
- [12] M.A. Finney, J. Forthofer, I.C. Grenfell, B.A. Adam, N.K. Akafuah, K. Saito, A study of flame spread in engineered cardboard fuelbeds: Part I: Correlations and observations, in: *7th International Symposium on Scale Modeling*, Hiroaki, Japan, 2013.
- [13] M.A. Finney, J.D. Cohen, J.M. Forthofer, S.S. McAllister, M.J. Gollner, D.J. Gorham, K. Saito, N.K. Akafuah, B.A. Adam, J.D. English, Role of buoyant flame dynamics in wildfire spread, *Proc. Natl. Acad. Sci. USA* 112 (2015) 9833–9838.
- [14] C.H. Miller, M.J. Gollner, Upward flame spread over discrete fuels, *Fire Saf. J.* 77 (2015) 36–45.
- [15] W. Cui, Y.-T.T. Liao, Experimental study of upward flame spread over discrete thin fuels, *Fire Saf. J.* 110 (2019) 102907.
- [16] G. Di Cristina, N.S. Skowronski, A. Simeoni, A.S. Rangwala, S. Im, Flame spread behavior characterization of discrete fuel array under a forced flow, *Proc. Combust. Inst.* 38 (2021) 5109–5117.
- [17] R. Bu, L. Shi, Y. Zhou, Identifying the criterion for discrete flame spread over single-row birch rods, *Fire Saf. J.* 120 (2021) 103116.
- [18] R. Bu, Y. Zhou, L. Shi, C. Fan, Experimental study on Combust. Flame spread characteristics in horizontal arrays of discrete fuels, *Combust. Flame* 225 (2021) 136–146.
- [19] R. Bu, Y. Zhou, C. Fan, Z. Wang, Understanding the effects of inclination angle and fuel bed width on concurrent flame spread over discrete fuel arrays, *Fuel* 289 (2021) 119924.
- [20] A. Carney, Y. Li, Y.-T. Liao, S. Olson, P. Ferkul, Concurrent-flow flame spread over thin discrete fuels in microgravity, *Combust. Flame* 226 (2021) 211–221.
- [21] Q. He, N. Liu, X. Xie, L. Zhang, Y. Zhang, W. Yan, Experimental study on fire spread over discrete fuel bed-part I: Effects of packing ratio, *Fire Saf. J.* 126 (2021) 103470.
- [22] Q. He, N. Liu, X. Xie, L. Zhang, J. Lei, Y. Zhang, D. Wu, Experimental study on fire spread over discrete fuel bed-Part II: Combined effects of wind and packing ratio, *Fire Saf. J.* 128 (2021) 103520.
- [23] A.N. Howell, E.L. Belmont, S.S. McAllister, M.A. Finney, An investigation of oxygen availability in spreading fires, *Fire Technol.* 59 (2023) 2147–2176.
- [24] Y. Zhang, J. Fang, F. Tian, L. Song, A.V. Singh, Upward flame spread over discrete thick fuels under mixed convection flow, *Fire Saf. J.* 135 (2023) 103723.
- [25] J.-L. Dupuy, Slope and fuel load effects on fire behaviour: laboratory experiments in pine needles fuel beds, *Int. J. Wildland Fire* 5 (1995) 153–164.
- [26] D.X. Viegas, Slope and wind effects on fire propagation, *Int. J. Wildland Fire* 13 (2004) 143–156.
- [27] M.A. Finney, J.D. Cohen, I.C. Grenfell, K.M. Yedinak, An examination of fire spread thresholds in discontinuous fuel beds, *Int. J. Wildland Fire* 19 (2010) 163–170.
- [28] F. Morandini, Y. Perez-Ramirez, V. Tihay, P.-A. Santoni, T. Barboni, Radiant, convective and heat release characterization of vegetation fire, *Int. J. Therm. Sci.* 70 (2013) 83–91.
- [29] F. Morandini, X. Silvani, Experimental investigation of the physical mechanisms governing the spread of wildfires, *Int. J. Wildland Fire* 19 (2010) 570–582.
- [30] L. Schneider, B. Betting, M. Patterson, N. Skowronski, A. Simeoni, Experimental study of fire spread through discontinuous fuels without flame contact, *Fire Saf. J.* 120 (2021) 103066.
- [31] M.A. Finney, J.D. Cohen, S.S. McAllister, W.M. Jolly, On the need for a theory of wildland fire spread, *Int. J. Wildland Fire* 22 (2013) 25–36.
- [32] S. McAllister, M. Finney, Autoignition of wood under combined convective and radiative heating, *Proc. Combust. Inst.* 36 (2017) 3073–3080.
- [33] S. Verma, M. Ahmed, A. Trouvé, The structure of line fires at flame scale, in: S. Goodrick, K. Speer (Eds.), *Wildland Fire Dynamics*, Cambridge University Press, 2022, Chapter 2.
- [34] B. Porterie, D. Morvan, J.C. Loraud, M. Larini, Firespread through fuel beds: Modeling of wind-aided fires and induced hydrodynamics, *Phys. Fluids* 12 (2000) 1762–1782.
- [35] D. Morvan, J.-L. Dupuy, Modeling of fire spread through a forest fuel bed using a multiphase formulation, *Combust. Flame* 127 (2001) 1981–1994.
- [36] D. Morvan, J.-L. Dupuy, Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation, *Combust. Flame* 138 (2004) 199–210.
- [37] W. Mell, M.A. Jenkins, J.S. Gould, P. Cheney, A physics-based approach to modelling grassland fires, *Int. J. Wildland Fire* 16 (2007) 1–22.
- [38] M. El Houssami, J.C. Thomas, A. Amorlette, D. Morvan, M. Chaos, R. Hadden, A. Simeoni, Experimental and numerical studies characterizing the burning dynamics of wildland fuels, *Combust. Flame* 168 (2016) 113–126.
- [39] Y. Perez-Ramirez, W.E. Mell, P.A. Santoni, J.B. Tramon, F. Bosseur, Examination of WFDs in modeling spreading fires in a furniture calorimeter, *Fire Technol.* 53 (2017) 1795–1832.
- [40] M. El Houssami, A. Amorlette, D. Morvan, R. Hadden, A. Simeoni, Framework for submodel improvement in wildfire modeling, *Combust. Flame* 190 (2018) 12–24.
- [41] N. Frangieh, D. Morvan, S. Meradji, G. Accary, O. Bessonov, Numerical simulation of grassland fires behavior using an implicit physical multiphase model, *Fire Saf. J.* 102 (2018) 37–47.
- [42] D. Morvan, G. Accary, S. Meradji, N. Frangieh, O. Bessonov, A 3D physical model to study the behavior of vegetation fires at laboratory scale, *Fire Saf. J.* 101 (2018) 39–52.
- [43] X. Sánchez-Monroy, W. Mell, J. Torres-Arenas, B.W. Butler, Fire spread upslope: Numerical simulation of laboratory experiments, *Fire Saf. J.* 108 (2019) 102844.
- [44] N. Frangieh, G. Accary, D. Morvan, S. Meradji, O. Bessonov, Wildfires front dynamics: 3D structures and intensity at small and large scales, *Combust. Flame* 211 (2020) 54–67.
- [45] M. Vanella, K. McGrattan, R. McDermott, G. Forney, W. Mell, E. Gissi, P. Fiorucci, A multi-fidelity framework for wildland fire behavior simulations over complex terrain, *Atmosphere* 12 (2021) 273.
- [46] J.L. Consalvi, B. Porterie, J.C. Loraud, A formal averaging procedure for radiation heat transfer in particulate media, *Int. J. Heat Mass Transfer* 45 (2002) 2755–2768.
- [47] C. Lautenberger, C. Fernandez-Pello, A model for the oxidative pyrolysis of wood, *Combust. Flame* 156 (2009) 1503–1513.
- [48] G. Rein, Smoldering combustion, in: *SFPE Handbook of Fire Protection Engineering*, fifth Ed., 2016, pp. 581–603, Chapter 19.
- [49] F. Richter, F.X. Jervis, X. Huang, G. Rein, Effect of oxygen on the burning rate of wood, *Combust. Flame* 234 (2021) 111591.
- [50] C. Lautenberger, C. Fernandez-Pello, Generalized pyrolysis model for combustible solids, *Fire Saf. J.* 44 (2009) 819–839.
- [51] OpenFOAM. www.openfoam.org.
- [52] F. Richter, G. Rein, A multiscale model of wood pyrolysis in fire to study the roles of chemistry and heat transfer at the mesoscale, *Combust. Flame* 216 (2020) 316–325.
- [53] A. Anca-Couce, N. Zobel, A. Berger, F. Behrendt, Smoldering of pine wood: Kinetics and reaction heats, *Combust. Flame* 159 (2012) 1708–1719.
- [54] M.M. Khan, J.L. De Ris, S.D. Ogden, Effect of moisture on ignition time of cellulosic materials, in: *Fire Saf. Sci., Proceedings of the 9th International Symposium*, 2008, pp. 167–178.

- [55] I. Haberle, Ø Skreiberg, J. Lazar, N.E.L. Haugen, Numerical models for thermochemical degradation of thermally thick woody biomass, and their application in domestic wood heating appliances and grate furnaces, *Prog. Energy Combust. Sci.* 63 (2017) 204–252.
- [56] M.M. Ahmed, Development of a Lagrangian-Eulerian modeling framework to describe thermal degradation of porous fuel particles in simulations of wildland fire behavior at flame scale, (Ph.D. thesis), University of Maryland, College Park, 2023.
- [57] T.L. Bergman, A.S. Lavine, F.P. Incropera, D.P. DeWitt, *Fundamentals of Heat and Mass Transfer*, eighth ed., Wiley, 2018.
- [58] S.W. Churchill, M. Bernstein, A correlating equation for forced convection from gases and liquids to a circular cylinder in crossflow, *J. Heat Transfer* 99 (1977) 300–306.
- [59] F. Nicoud, F. Ducros, Subgrid-scale stress modelling based on the square of the velocity gradient tensor, *Flow Turbul. Combust.* 62 (1999) 183–200.
- [60] B.F. Magnussen, B.H. Hjertager, On mathematical modeling of turbulent combustion with special emphasis on soot formation and combustion, *Proc. Combust. Inst.* 16 (1976) 719–729.
- [61] J. Chai, S. Patankar, Discrete-ordinates and finite-volume methods for radiation heat transfer, in: *Handbook of Numerical Heat Transfer*, John Wiley & Sons, 2006, pp. 297–323.
- [62] S.J. Ritchie, K.D. Steckler, A. Hamins, T.G. Cleary, J.C. Yang, T. Kashiwagi, The effect of sample size on the heat release rate of charring materials, in: *Fire Saf. Sci., Proceedings of the 5th International Symposium*, 1997, pp. 177–188.
- [63] P. Andrews, *The Rothermel Surface Fire Spread Model and Associated Developments: A Comprehensive Explanation*, General Technical Report RMRS-GTR-371, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2018.
- [64] G.M. Byram, Combustion of forest fuels, in: K.P. Davis (Ed.), *Forest Fire Control and Use*, McGraw-Hill, 1959, Chapter 3.
- [65] L.-M. Yuan, G. Cox, An experimental study of some fire lines, *Fire Saf. J.* 27 (1996) 123–139.
- [66] M.A. Finney, T.P. Grumstrup, Effect of flame zone depth on the correlation of flame length with fireline intensity, *Int. J. Wildland Fire* 32 (2023) 1135–1147.
- [67] U. Wickström, The adiabatic surface temperature and the plate thermometer, in: *Fire Saf. Sci., Proceedings of the 10th International Symposium*, 2011, pp. 1001–1012.
- [68] J.L. Torero, J.I. Gerhard, M.F. Martins, M.A.B. Zanon, T.L. Rashwan, J.K. Brown, Processes defining smouldering combustion: Integrated review and synthesis, *Prog. Energy Combust. Sci.* 81 (2020) 100869.