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Dynamics of wildland fires and their impact on structures

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Abstract

A physics-based forest fire model, based on a multiclass description of two-phase flow, is developed to study fire behavior and the response of structures to fire-induced thermal stress. The model is three-dimensional and considers the coupled physicochemical processes that take place in both phases: the thermal degradation of organic matter and glowing combustion of the char, as well as turbulence, flaming combustion, soot formation, and radiation for the gas phase. Model results are compared with data from two specially designed experiments. The first refers to a back-wind prescribed burning over a 900 m^2 area of steep-slope terrain. The model predicts not only the mean rate of fire spread, but also the convex shape of the head-fire front resulting from three-dimensional effects. In the second experiment, attention is focused on the thermal impact of a fire-exposed structural element placed in a wind tunnel. The predicted fire-front trajectory is shown to be in good agreement with measurements as well as the temperature level and the location of the exposed area of the structure.

Keywords: Wildland fire; Wildland–urban interface; Fire behavior model; Physics-based model; Fire spread; Fire-exposed structure

1. Introduction

The aim of this article is twofold: first, to model fire spread through heterogeneous fuel beds in order mainly to gain a better understanding of the behavior of wildland fires in the near-field region; second, to predict the thermal impact of structural elements exposed to such fires in wildland–urban interface (WUI) areas.

Simple observations of the spread of wildland fires reveal that the bed may be schematically divided into three areas, as shown in Fig. 1. In the heating stage, fuel material decomposes into volatile gases. These pyrolysis products convect and diffuse outward and mix with air to form a combustible mixture ahead of the flame leading edge. Then this mixture is ignited by the flame. A free turbulent radiating sooty diffusion flame is then formed. At the end of the pyrolysis process, flaming combustion ceases and, if oxygen is present and the temperature sufficiently high, glowing combustion of the char occurs. The rate of fire spread (i.e., the rate of translation of the boundary between regions 1 and 2 in Fig. 1) is dependent on the capacity of the flame and burning region of the fuel bed to supply a sufficient amount of heat to pyrolyze the fuel and to ignite the pyrolysis product/oxidizer mixture ahead of the flame. The heat transfer from the flame to the

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Nomenclature

a	absorption coefficient, m^{-1}
A_k	specific wetted area of the solid-phase class k, $\alpha_k\sigma_k$, m^{-1}
C_p	specific heat, $J\,kg^{-1}\,K^{-1}$
f_{v_s}	soot volume fraction
F_i	drag force component in the ith direction
g_i	gravity acceleration component in the ith direction
G	average incident radiation, $W\,m^{-2}$
I	radiative intensity, $W\,m^{-2}\,sr^{-1}$
I_b	black-body radiative intensity, $I_b(T) = \sigma T^4/\pi$, $W\,m^{-2}\,sr^{-1}$
h	enthalpy, $J\,kg^{-1}$
Δh	heat of reaction, $J\,kg^{-1}$
k	turbulent energy, $m^2\,s^{-2}$
L	latent heat, $J\,kg^{-1}$
m_k	mass of the solid-phase class k per unit volume, $\alpha_k\rho_k$, $kg\,m^{-3}$
$\dot{m}_k$	rate of mass loss by thermal degradation and combustion of the solid-phase class k, $kg\,m^{-3}\,s^{-1}$
p	pressure, Pa
Pr	Prandtl number, $\mu_g C_p/\lambda_g$
$\mathbf{q}$	heat flux vector, $W\,m^{-2}$
Q	energy influx, $W\,m^{-3}$
s, s_1	stoichiometric ratios
T	temperature, K
u_i	gas velocity component in the ith direction
x_j	or x, y, z Cartesian coordinates
Y_α	mass fraction of species α

Greek symbols

α	phase volume fraction
δ_{ij}	Kronecker delta
ε	dissipation rate of k, $m^2\,s^{-3}$
λ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
μ	viscosity, $kg\,m^{-1}\,s^{-1}$
ρ	density, $kg\,m^{-3}$
σ	Stefan–Boltzmann constant, $W\,m^{-2}\,K^{-4}$
σ_k	surface-area-to-volume ratio of a solid particle, m^{-1}
σ_ϕ	turbulent Prandtl/Schmidt number for ϕ
ϕ	any transported variable
$\dot{\omega}_\alpha$	rate of production of the species α due to chemical reactions, $kg\,m^{-3}\,s^{-1}$
$\boldsymbol{\Omega}$	directional vector of radiative intensity

Subscripts and superscripts

c	convective/conductive
g	gas phase
k	solid-phase class k
pyr	pyrolysis products
r	radiative
α	species

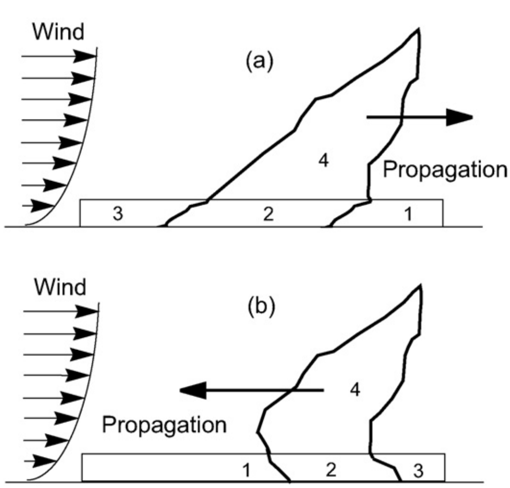

Fig. 1. Structure of the fire front propagating through a fuel bed: (a) wind-driven propagation, (b) back-wind propagation. (1) Unburnt heated fuel (drying, slow pyrolysis), (2) burning zone (intense pyrolysis, homogeneous and heterogeneous reactions, flameless smoldering combustion), (3) ashes, (4) turbulent luminous free flame.

unburnt solid material is also strongly dependent on the flame outline, which in turn depends on the dynamic structure of the gas flow. In a wind-driven configuration (Fig. 1a), the flame is very close to the fuel bed during the thermal degradation process, which favors heat transfer from the flame to the unburnt fuel. This mode of spread is therefore generally fast, unlike the back-wind fire spread mode, in which the gas flows in the direction opposite to the spread (Fig. 1b).

Following the classification of Weber [1], the present model belongs to the class of physical models initiated by Grishin [2] (see also the monograph of Grishin published in [3] and also more recently [4]). It differs from statistical and empirical models in that it accounts for each mechanism of heat transfer individually and predicts not only the spread rate of the fire but also its complete behavior. Unlike statistical and empirical models, physics-based simulations require a huge amount of computational resources as well as a large number of data difficult to practically obtain. This explains why the two first have allowed developing operational tools for real fire situations, whereas the last are mainly considered as knowledge