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Computational smoldering combustion: Predicting the roles of moisture and inert contents in peat wildfires

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Abstract

Smoldering combustion is the slow, low-temperature, flameless burning of porous fuels and the most persistent type of combustion. It is the driving phenomenon of wildfires in peatlands, like those causing haze episodes in Southeast Asia and Northeast Europe, but is poorly understood. In this work, we develop a comprehensive 1-D model of a reactive porous media, using the open-source code Gpyro, to investigate smoldering combustion of natural fuels with an emphasis on the roles of the moisture and inert contents. The model solves the species, momentum, and energy conservation equations and includes heterogeneous chemical reactions. A previously developed 5-step reaction scheme for peat, including evaporation of water, is adopted to describe the drying, thermal and oxidative degradation during the smoldering combustion. The model predicts the transient temperature, species, and reaction profiles during ignition, spread, and extinction. The predicted smoldering thresholds related to the critical moisture and inorganic contents for ignition show a good agreement with the experimental results in the literature for a wide range of peat types and organic soils. The influences of the kinetic parameters, physical properties, and ignition protocol are investigated. This is the first time that a physics-based model of smoldering peat fires is developed, thus helping to understand this important natural and widespread phenomenon.

Keywords: Peat wildfires; Smoldering combustion; Computational; Drying; Smoldering thresholds

1. Introduction

Smoldering combustion is the slow, low-temperature, flameless burning of porous fuels and the most persistent type of combustion [1]. Smoldering is the dominant phenomenon in megafires in natural deposits of peat which are the largest and longest burning fires on Earth. These fires contribute considerably to global greenhouse gas emissions, and result in widespread destruction of ecosystems and regional haze events (e.g. recent megafires in Southeast Asia, North America and Northeast Europe) [2]. It is an emerging research topic in climate change mitigation but is poorly understood. For example, during the 1997 extreme haze event in Southeast Asia, peat fires emitted the equivalent to 13–40% of the global man-made greenhouse gas emissions of that year [3]. Rein [2] has pointed out that the atmospheric release of ancient carbon from the soil and the

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Nomenclature

A	pre-exponential factor
c_p	heat capacity
d_p	characteristic pore size
C	heat of complete oxidation
E	activation energy
h	enthalpy
h_c	convective coefficient
h_m	mass-transfer coefficient
k	thermal conductivity
K	permeability
$\dot{m}''$	mass flux
n	heterogeneous reaction order
P	pressure
R/R_s	universal/specific gas constant
S	particle surface area
t	time
T	temperature
Y	mass fraction
z	distance
IC/MC	inorganic/moisture content

Greeks

γ	radiative conductivity coefficient
ε	emissivity
ν	viscosity/stoichiometric coefficient
ρ	bulk density (mass concentration)
ρ_s	solid density, $\rho/\rho_s = 1 - \psi$
σ	Stefan–Boltzmann constant
χ	fraction factor
ψ	porosity
$\dot{\omega}$	reaction rate

Subscripts

0	initial
$\alpha/\alpha o$	α-char/α-char oxidation
$\beta/\beta o$	β-char/β-char oxidation
a	ash
d/f	destruction/formation
dr	drying
g	gas
i	condensed species number
j	gaseous species number
k	reaction number
$p/po/pp$	peat/peat oxidation/peat pyrolysis
w	water

sensitivity of peat ignition to higher temperatures and drier soils could create a positive feedback mechanism for climate change.

Peat can hold a wide range of moisture contents (MC[1]), ranging from 10%, under drought conditions, to in excess of 300%, under flooded conditions [4]. Water represents a significant energy sink, and furthermore natural or anthropogenic-induced droughts are found to be the leading cause of smoldering megafires [5,2]. Therefore, soil moisture is the single most important property governing the ignition and spread of smoldering wildfires [5–7]. The critical moisture content (MC_c) for initiating smoldering of various boreal peat has been measured in the range 40–150% in dry basis [7,8]. Drier than this threshold, peat becomes susceptible to smoldering. The second most important property is the soil inorganic content (IC[1]). As experimentally found by Frandsen [6,7], there is a decreasing quasi-linear relationship between MC_c and IC_c: soil with a high IC can only be ignited at low MC. Mineral matter acts as a heat sink but also enhances the heat transfer via its higher heat conductivity. After moisture and inorganic contents, other important properties are bulk density, porosity, flow permeability and organic composition [2].

The spread of smoldering fires is controlled by heat and mass transfer processes in a reactive porous media. The computational studies on smoldering combustion in the literature have only included three fuels: cellulose [1,9], polyurethane foam [1,8] and char [10], simulated with chemical schemes of different complexity, including 1 [10], 3 [1] or 5 [8] steps. Ohlemiller [1] reviewed the early attempts on simulating smoldering combustion and provided the governing equations in general form. Rein et al. [8] numerically solved the 1-D smoldering combustion of polyurethane foam under forced flow with a 5-step kinetics, and the results were compared to microgravity experiments in both opposed and forward propagation modes. He et al. [10] developed a 1-D model to solve the in-depth spread of smoldering for char with 1-step chemistry and compared it to the experiments. Previous studies have not considered simulations of peat fires or the drying process.

In this work, we use a comprehensive 1-D model based on Gpyro [11] and a previously developed 5-step kinetics (including drying) for peat kinetics [12] to investigate the ignition and spread of smoldering in a bed of peat and other organic soils. Prediction of the smoldering

[1] Moisture content (MC) is defined in dry basis as the mass of water divided by the mass of a dried soil sample, expressed as %. Inorganic content (IC < 100%) is defined in dry basis as the mass of soil inorganic matter (minerals) divided by the mass of a dried soil sample, expressed as %.