Smouldering combustion of peat in wildfires: Inverse modelling of the drying and the thermal and oxidative decomposition kinetics ☆

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ABSTRACT

Smouldering combustion is the driving phenomenon of wildfire in peatlands, like those causing haze episodes in Southeast Asia and Northeast Europe. These are the largest fires on Earth and an extensive source of greenhouse gases, but poorly understood, becoming an emerging research topic in climate-change mitigation. In this work, a series of multistep heterogeneous kinetics are investigated to describe the drying and decomposition in smouldering combustion of peat. The decomposition schemes cover a range of complexity, including 2, 3 or 4-step schemes, and up to 4 solid pseudo-species. The schemes aim to describe the simultaneous pyrolysis and oxidation reactions in smouldering fires. The reaction rates are expressed by Arrhenius law, and a lumped model of mass loss is used to simulate the degradation behaviour seen during thermogravimetric (TG) experiments in both nitrogen and air atmospheres. A genetic algorithm is applied to solve the corresponding inverse problem using TG data from the literature, and find the best kinetic and stoichiometric parameters for four types of boreal peat from different geographical locations (North China, Scotland and Siberia). The results show that at the TG level, all proposed schemes seem to perform well, with a high degree of agreement resulting from the forced optimization in the inverse problem approach. The chemical validity of the schemes is then investigated outside the TG realm and incorporated into a 1-D plug-flow model to study the reaction and the species distribution inside a peat smouldering front. Both lateral and in-depth spread modes are considered. The results show that the drying sub-front is essential, and that the best kinetics is the 4-step decomposition (one pyrolysis, and three oxidations) plus 1-step drying with 5 condensed species (water, peat, α-char, β-char, and ash). This is the first time that the smouldering kinetics and the reaction-zone structure of a peat fire are explained and predicted, thus helping to understand this important natural and widespread phenomenon.

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1. Introduction

Smouldering combustion is the slow, low-temperature, flameless burning of porous fuels [1,2] and the most persistent type of combustion phenomena [3]. It is sustained by the heat released when oxygen directly attacks the surface of a solid fuel [1]. It is different from the high-temperature homogenous flaming combustion, but especially common in solid fuels with a tendency to char. Many materials can sustain a smouldering fire, including synthetic fuels such as polyurethane foam or cellulosic insulation, and natural fuels like coal or soils rich in dead organic matter, like peat.

Peatlands, made by the natural accumulation of partially decayed vegetation, are the most affected ecosystem by smouldering fires, both in frequency and size. Peat forms organic soil layers of carbon older than 10 thousand years and of depths upon dozens of meters. They are the largest reserves of terrestrial carbon and important ecosystem for a wide range of wildlife habitats, supporting biological diversity, and hydrological integrity [4].

Because of this vast accumulation of natural fuel, once ignited, smouldering peat fires burn for very long periods of time (e.g., months and years) despite extensive rains, weather changes, or fire-fighting attempts. These are the largest fires on Earth and large contributors of greenhouse gases [3,5]. Peat fires occur with some frequency worldwide in tropical, temperate and boreal regions (e.g., Indonesia, Canada, Florida, British Isles, and Siberia). During the 1997 extreme haze event in Southeast Asia, the greenhouse-gas emission from peat fires was equivalent to 13–40% of the global man-made emissions of that year [4]. More recent figures

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Nomenclature

A	pre-exponential factor
Da	Damköhler number
E	activation energy
h_0, h_b	original/burning height
L	characteristic thickness of smouldering front
k	heating rate
$m/[m]$	mass fraction (wet basis/dry basis)
$\dot{m}/[\dot{m}]$	mass-loss rate (wet basis/dry basis)
n	reaction order
R	universal gas constant
T	temperature
S	smouldering spread rate
w	weight coefficient
Y_{O_2}	oxygen mass fraction in gas phase

Greeks symbols

α	thermal diffusivity
γ	relative importance in the fitness
δ	thickness of reaction zone
$\dot{\theta}$	non-dimensional reaction rate
ν	stoichiometric coefficient
ξ	non-dimensional spatial location
Π	non-dimensional temperature
ρ	density
τ	characteristic reaction time
Φ	objective function

$\dot{\omega}$	reaction rate

Subscripts

0	initial
α	α-char
αo	α-char oxidation
β	β-char
βo	β-char oxidation
a	ash
cal	calculation
c	char
co	char oxidation
d	in-depth spread
dr	drying
exp	experiment
g	gas phase
i	solid species number
k	reaction number
l	lateral spread
p	peat
pd	peat decomposition
po	peat oxidation
pp	peat pyrolysis
s	solid phase
w	water

estimate that the average emission from peat fires is roughly equivalent to 15% of the man-made emissions [6]. Moreover, the atmospheric release of ancient carbon from the soil and the sensitivity of peat ignition to higher temperatures and drier conditions create a positive feedback mechanism to climate change [3].

For most smouldering fires and under typical conditions, two mechanisms control the rate of spread: the oxygen supply and the heat losses [1]. At the micro scale, smouldering takes place on the surface of a solid fuel, and at the macro scale, it is a bulk phenomenon affecting a porous fuel bed at large. By reacting on the surface of the pores, the fire can penetrate deep into the bed of fuel if oxygen can be transported from a free surface (e.g., open atmosphere, crack or channel). Most peat fires are initiated on the top surface of the fuel bed [3]. The fire then spreads both laterally and in-depth, dominated by forward smouldering (Fig. 1). The lateral spread is enhanced by a direct supply of atmospheric oxygen so its rate is significantly faster than the in-depth spread. It leads to a void in the general shape of an ellipsoid or pan. When the uppermost layer is exposed to wind, the combustion is quenched by heat losses leaving a thin layer of charred material on the very top while smouldering continues just below it. As the fire propagates deeper, a layer of ash also builds up. These two layers, observed often in the field [7], act like an heat insulator to support the reaction front below.

The spread of smouldering fires is dominated by heat and mass transfer processes in a reactive porous media [1,8,9]. Among these mechanisms, the reactivity of peat in the form of a valid and quantified reaction scheme is currently missing. Knowledge of heterogeneous combustion reactions is less developed than homogenous gas-phase kinetics [10,8]. One of the major reasons for this is that it is difficult to experimentally identify the various solid-phase species, especially for a complex organic mixture like peat [11]. Typically, kinetic schemes with just a few global steps and pseudo species are used. Current knowledge shows that smouldering combustion involves simultaneous and competing

pyrolysis and oxidation reactions [1,3,9,12]. The endothermic pyrolysis reactions decompose the virgin fuel into pyrolysate gases and char.

Various kinetic schemes of different complexity have been proposed for smouldering combustion. Ohlemiller [1] proposed a 3-step and 3-species scheme, including one pyrolysis and two oxidations, as general scheme for any smoulder-prone fuel. Kashiwagi and Nambu [13] quantified the kinetic parameters of this scheme for cellulose using thermogravimetric analysis (TGA) on small samples (~mg scale) under nitrogen and air atmospheres. Rein et al. [9] studied polyurethane foam, and extended Ohlemiller's scheme to 5-step and 4-species kinetics (two pyrolysis and three oxidations). This extended scheme allows explaining the reaction structure of a smouldering front in both forward and opposed propagation. In doing so, Rein et al. [9] developed a methodology where a genetic algorithm
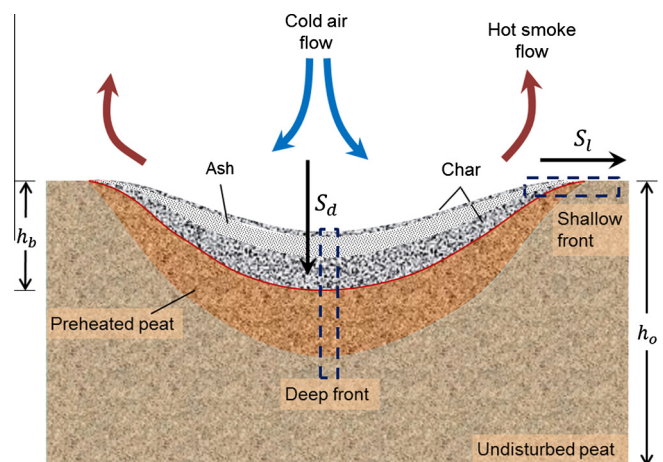

Fig. 1. Schematic diagram of the lateral and in-depth spreads of a smouldering wildfire in a layer of peat.