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Two-dimensional model of smouldering combustion using multi-layer cellular automaton: The role of ignition location and direction of airflow

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ABSTRACT

Smouldering combustion is one of the most common and persistent fire hazards of reactive porous media, such as biomass. In this work, a two-dimensional multi-layer cellular automaton has been developed to study the process of smouldering and the roles of both the ignition location and the direction of airflow for generic biomass. Three different configurations are studied: line front, with forward and opposed airflow respectively, and radial front. The first two configurations simulate ignition of one edge of the sample, while the radial front simulates ignition of a spot at the centre of the sample. The resulting spread patterns of line *vs.* radial front are significantly different. Furthermore, when smouldering occurs with similar characteristics, where both line front and radial front are self-sustained, the smouldering radial front has a higher growth rate than the line front. However, in the studied cases where enough oxygen is always available for oxidation, the direction of the airflow does not influence the spread of the smouldering front, and the line front with forward and opposed airflow present similar behaviour. Finally, two non-zero minimum values have been detected for self-sustained spread according to the moisture of the fuel (probability of drying) and its tendency for thermal degradation (probability of pyrolysis). This model provides a powerful but simple way of reproducing the complex dynamics of smouldering processes which can be used to investigate different scenarios.

1. Introduction

Smouldering combustion is the slow, low temperature, flameless burning of porous fuel [1] and is the most persistent type of combustion phenomena [6]. Smouldering is one of the most hazardous phenomena worldwide, including residential fires, fire deaths [2,3] and megafires in natural deposits of peat and coal [4].

Current understanding on smouldering combustion is limited, and considerably less advanced than flaming combustion, mainly because the characteristic temperature, spread rate and power of smouldering combustion are fundamentally different to flaming combustion [5,6].

For most smouldering fuels under typical conditions, the two mechanisms controlling the rate of spread are the oxygen supply and the heat transfer [1]. Also, smouldering can be characterized by its direction of propagation relative to the direction of the oxygen supply. Forward propagation occurs when the oxygen supply is moving along the spread direction of the smoulder front. Opposed propagation occurs when the oxygen supply is moving opposite to the spread direction of the smoulder front.

The process of smouldering ignition requires the supply of heat, and is governed by heat transfer and fuel kinetics, with the oxygen supply rate playing a secondary role [6]. Above a critical threshold of heat supply, the temperature increase initiates endothermic pyrolysis, which is followed by the onset of exothermic oxidation. When the heat released by oxidation is high enough to balance the heat required for the endothermic processes, propagation occurs and the reaction might become self-sustaining and only then will oxygen supply rate play an important role [6].

Conditions sufficient to yield smoulder initiation might not be sufficient for self-sustained spread away from the ignition region. If the external heat supply continues, assisted propagation is possible. Otherwise, once the external heat supply ceases, the smouldering reaction will either be self-sustained or lead to extinction [6].

Several investigations have been conducted in order to explain numerically the behaviour of smouldering through its governing equations [7–9]. These modelling methods, more traditional, rely on solving the conservation equation in partial differential equation (PDE) form [10,11]. However, due to the complexity of the process and the interest in completely understanding it, new methodologies are welcome. Cellular automata is an ideal methodology for modelling

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emergent complex processes through simple rules [12].

A cellular automaton is a mathematical model which consists of a set of cells usually distributed in a matrix form [13]. Firstly introduced by von Neumann in 1966 [14], this methodology has been extensively used to model complex systems [15]. It has been considered a suitable alternative to differential equations for many physical systems and processes, also in the field of environmental modelling and, in particular, for simulating fire spread [16,17].

Wolfram [15] defined five fundamental characteristics of discrete cellular automata that show the suitability of modelling smouldering combustion through this methodology: (1) they consist of a discrete lattice of cells, (2) cellular automaton evolve in discrete time steps, (3) each cell takes on a finite set of possible values, (4) the value of each cell evolves according to some rules mimicking the process under consideration, (5) the rules for the evolution of a cell depend only on a local neighbourhood of sites around it. By relaxing (3) such that the state variables might take values in a continuous range, the associated cellular automaton is often referred to as a lattice map. By comparing these characteristics with a smouldering combustion process, it can be observed that this process can be discretized both in space and in time, and the evolution of drying, pyrolysis and oxidation can be defined with stochastic rules depending on the changes that occurs on the surroundings of each discrete site.

Belcher *et al.* [18] were the first to develop a cellular automaton for smouldering. Their model was a one-layer cellular automaton. We have built on this and produced a cellular automaton model taking into account the chemistry of smouldering process and the mechanisms of heat loss and oxygen supply. Our model is defined as a multi-layer model, where each mechanism is defined in a different layer. The model represents the complete smouldering combustion of a generic biomass and predicts the self-sustained fire and spread dynamics.

2. Methodology

The essential processes of smouldering have been implemented by a multi-layer cellular automaton, incorporating the probability rate for each step. Probability rate means the extent to which something is likely to happen per time unit, so it represents the easiness of occurrence of the process. In its simplest representation, these steps are [6]:

1st step, Drying:

$$\text{Fuel (wet)} + \text{Heat} \rightarrow \text{Fuel (dry)} + H_2O \quad (1)$$

Drying consists of removing the water that is contained in the fuel by applying a certain amount of heat. Therefore, the drying process probability rate mainly depends on the moisture content of the fuel, i.e. when the fuel is wetter, it is less probable for it to dry within each time step. The drying process is crucial in determining the ignition and spread of smouldering fires [19,20].

2nd step, Pyrolysis:

$$\text{Fuel (dry)} + \text{Heat} \rightarrow \text{Char} + \text{Pyrolyzate} \quad (2)$$

Pyrolysis means to break with heat, and it is the thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen (above 200 °C for organic fuels). It involves simultaneous and irreversible changes of chemical composition and physical parameters. The pyrolysis probability rate is related with the resistance to degrade of the fuel.

3rd step, Oxidation:

$$\text{Char} + O_2 \rightarrow \text{Ash} + \text{Heat} + CO_2 + H_2O + \text{other gases} \quad (3)$$

Oxidation is the chemical reaction at elevated temperatures over 350 °C for organic fuels that consumes oxygen and produces heat. The probability rate of oxidation is directly related to the organic content of the fuel.

With these processes in mind, a cellular automaton was developed. As a simplification, we considered a two-dimensional situation ignoring the height of the fuel. Two-dimensional cellular automata are discrete dynamic systems formed by a finite number of identical objects called cells, which are arranged uniformly in a two-dimensional space [21]. They have an associated state that changes at every step of time according to pre-fixed rules, mimicking the relevant processes.

This model is developed as a generic cellular automaton describing the smouldering process of a biomass fuel. Hence, all the parameters that characterize the model are non-dimensional parameters, such as the width of the cell, the time step, or the probability ratios that range from 0 to 1.

The model is stochastic and is formed by three interacting “layers” or matrices that characterize the fuel, the heat and the oxygen according to the processes described in Eqs. (1)–(3), respectively. The software implementation of the proposed model was written in the Matlab programming language.

For developing this model, the three-step combustion kinetics given in Eqs. (1)–(3) have been used where we include the essential role in the process of fuel, heat and oxygen.

The present model studies the post-initiation behaviour of smouldering, where the initiation due to an external heat source is not taken into account.

Each one of the three parts of the process (fuel, heat and oxygen) was defined in a layer (matrix) each one presenting internal rules and different interactions with the other two layers, as explained in the present section.

In the proposed model, the time step is equal to the time needed for one cell to change its state. The state of a cell at time t+1 is affected by the states of the cells in its neighbourhood at time step t and its own state at time t. Classically, there are two main types of neighbourhoods

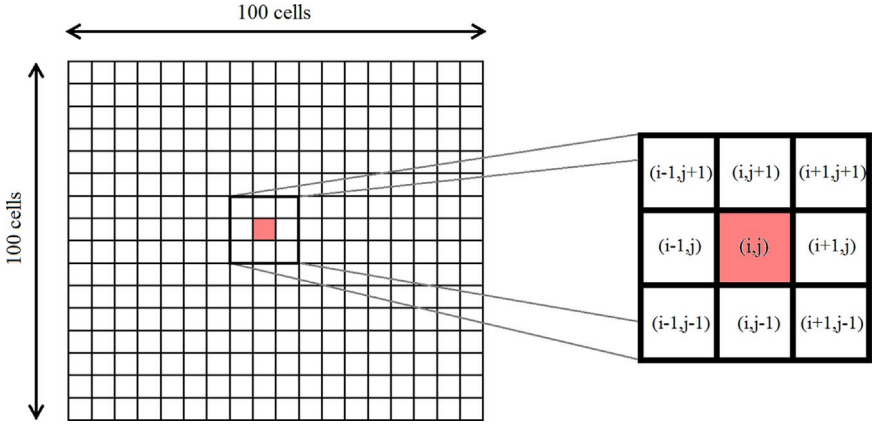

Fig. 1. The Moore neighbourhood of the red cell (i,j) in a square is the eight cells indicated with their coordinates in the zoom-in figure to the right.