Towards a Stochastic Cellular Automata Model of Log Wood Combustion

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Abstract. Describing the combustion of log wood and others solid fuels with complex geometry, considerable water content and often heterogenous structure is a nontrivial task. Stochastic Cellular Automata models offer a promising approach for modelling such processes. Combustion models of this type exhibit several similarities to the well-known forest fire models, but there are also significant differences between those two types of models. These differences call for a detailed analysis and the development of supplementary modeling approaches. In this article we define a qualitative two-dimensional model of burning log wood, discuss the most important differences to classical forest fire models and present some preliminary results.

Keywords: cellular automata, stochastic modeling, combustion

1. Introduction: The Role of Log Wood

Biomass is an important source of renewable energy; the efficient use of biomass will be essential to achieve the transition to a lifestyle based on renewable resources. In order to reach the European 20-20-20 goals [1], about half of the demand for renewable energy will have to be covered by biomass. More than half of this amount will presumably be used in domestic small-scale combustion systems.

While pellet technology – promising better control and lower emissions than traditional wood combustions – is on the rise, log wood is still an important fuel and will presumably remain to be so for decades to come. A main advantage of log wood is an economic one: Since less processing is required, log wood has a lower price than pellets. Also stoves tend to be cheaper. At the same time, less volume is needed for storing wood logs than for storing wood chips, an even cheaper renewable fuel. Also the handling of wood logs is easier than that of wood chips.

The combustion of wood logs, however, is a complex process which involves transport processes, chemical reactions and heat transfer processes within complex geometry. There has been put quite some effort in the development of models for combustion of woody particles, in particular shrinking-core and reacting-core models [2, 3, 4, 5] and CFD-related approaches based on partial differential equations [6, 7]. These models grasp some important aspects of wood combustion, but they cannot (yet) incorporate the often complex geometry of wood logs. Complementary modeling approaches, as the one presented in this article, may help to improve this situation.
Figure 1. Sketch of the Cellular Automata approach on a $[5 \times 5]$-grid for seven time steps.

2. Cellular Automata: Forest Fire Models and Beyond

Cellular Automata (CA) are recognized as an important modeling tool in many fields of science. In the CA approach, space is defined as an $N$-dimensional grid (with $N = 1$ or $N = 2$ being the most popular choices) of cells. Time is defined as a sequence of (equidistant) time steps.

The cell states are usually chosen from a limited set of states. Time evolution is described by simple but universal update rules, see fig. 1. These rules typically only make use of the current cell state and the states of cells in a small neighbourhood. This results in a limited speed of the transport of information, naturally implementing the principle of locality.

A particularly famous class of CA-based models are forest fire models, which can be formulated as deterministic [8, 9, 10] or stochastic models [11]. These models may exhibit a number of fascinating properties, including critical behaviour and self-organized criticality. With suitable re-interpretation, these models can also be applied to disease spreading and other propagation phenomena.

At first glance, such forest fire models may seem well-suited to describe, at least qualitatively, also the combustion of solid fuels. At second glance, however, there are some striking differences between those systems:

- Oxygen supply is rarely a limiting factor for forest fires. As a consequence, fire propagation is most efficient for a high density of “forest” cells. In contrast to that, oxygen supply is critical in the log wood case, in particular in the ignition phase. A large surface-to-volume ratio is beneficial for ignition; a “fragmented” piece of wood has a much higher chance of catching fire than a solid block. Without sufficient oxygen supply, one may have charring, but not burning of the char.
- Forest fires are typically modeled via nearest-neighbour interactions. This is reasonable since a cell usually describes a patch of vegetation of considerable size, and it is known that firebreaks can indeed be an efficient way to stop the propagation of forest fires. (Still, in situations with strong wind, flying sparks can lead to fire propagation which defies a description with nearest-neighbour interaction.)

For wood combustion, radiation effect can be important, and ignition does not necessarily depend on direct contact. Thus the local nearest-neighbour-approach will have to be supplemented by an additional mechanism for fire propagation.

3. A CA Model for Log Wood Combustion

Wood combustion is a complex process which is composed of heat-up, drying, pyrolysis and char burnout. A detailed modeling of the physical and chemical processes tends to become quite involved [12]. In this article we aim at a simple effective model which still yields a reasonable qualitative description of the key processes.
The present model is formulated in terms of two matrices: \( W \) encodes the status of the woody fuel, \( w_{i,j} \in \{-2, -1, 0, \ldots, 8, 9\} \). \( E \) encode the density of discrete “energy packages” which describe in a combined way excess heat and temperature level, \( e_{i,j} \in \{0, 1, 2, \ldots\} \). Thermal conversion of fuel is described by a transition \( w_{i,j} = k \to k + 1 \) which changes the energy content \( e_{i,j} = n \to n + E_{\text{released}}^{k \to k+1} \). A specific transition \( k \to k + 1 \) may require a minimum energy content \( E_{\text{min},k} \), may require an empty neighbour cell (if oxygen or empty space is needed for the underlying process) and may occur only with a certain probability \( p_{k \to k+1}^{\text{trans}} \). The list of cell states is given in tab. 1.

Most of the parameters are rough estimates at the present stage, but a fundamental requirement for the model to make sense is the condition \( \sum_{k=1}^{9} E_{\text{released}}^{k \to k+1} > 0 \). This is necessary in order to describe an exothermic reaction which can sustain itself.

The energy packages are subject to a biased random walk, with the probability to move upwards (0.17) being slightly larger than the probability to move left or right (0.15 each) and noticeably larger than the probability to move downwards (0.13). Ignition is initiated by an external energy input at one corner of the grid during the first few timesteps.

The model also contains an extremely simplified description of gravity. If a fuel structure is not connected to stone \( (w_{i,j} = -1) \), the whole structure moves downwards by one spatial step per timestep. Any effects of torque or other stability issues are not yet included.

A snapshot of a sample simulation run is shown in fig. 2, the net energy release during such a run in fig. 3.

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Figure 2. Snapshot of a typical simulation run on a [40 × 40]-grid in a combined representation of $W$ and $E$. The fire has been ignited by external energy input in the lower left corner and now spreads, creating a zone of dried and charred wood. The color code is defined in tab. 1.

Figure 3. Net energy released in drying and conversion processes for a typical simulation run on a [40 × 40]-grid. Since short-time fluctuations are large, the time series has been smoothed by weighted averaging over consecutive values. Note that the energy release is negative in the first phase (when external energy input is required for ignition) and that even later it can approach and even drop below zero. Such events may indicate critical phases in the combustion process where the fire is at risk of being extinguished.

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