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# A mathematical model to predict the heating-up of large-scale wood piles

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ABSTRACT

A mathematical model to predict the heating-up in open air wood chip piles has been developed. This model includes the heat production from chemical, physical and microbial exothermal processes. In the manuscript the laboratory experiments needed to develop and validate the model are described. In addition, temperature and gas concentrations were measured in two large-scale wood piles (volumes bigger than 1000 $m^3$), in order to provide the applicability of the model to large-scale scenarios. The predictions of the model and the large-scale experimental data showed good agreement concerning the maximum temperature reached inside an open air wood pile. Special attention has been devoted to the microbial processes, since they proved to be the most important cause of heat production in the early stages of storage. This work is intended to help in predicting and thus avoiding possible self-ignition scenarios for this type of wood storage.



## 1. Introduction

The storage of wood chips in large open air piles with thousands of tons of material is susceptible to the self-ignition of the bulk material, as it has already been frequently reported, for example in Rothenburg (2000) and in Traunreut (2005). Being nowadays scrap or rest wood from the forest industry one of the main sources of renewable fuels and in the perspective of the prognosticated increase in the use of renewable energies in the near future by Nitsch (2007), the number of open air wood storages and thus the possibility of their self-ignition seems destined to grow in the next years.

Undesired fires from self-ignition bring important economical losses and cause emission of carbon dioxide and of toxic gases, like carbon monoxide through incomplete combustion. Furthermore, since the energy production must be guaranteed, the losses in the renewable energy source would be possibly compensated with fossil fuels: this gives rise to additional carbon dioxide emissions. Prevention of the self-ignition in stored wood is therefore an economical and safety relevant issue. Nevertheless, only few studies, see Bergman and Nilsson (1971), Ernstson and Rasmuson (1993), Sampson and McBeath (1987) and Springer and Hajny (1970) dealt with the heating-up process inside open air wood piles. This work aims to improve the knowledge in the self-ignition of wood piles, in order to prevent possible fires.

The reasons for self-ignition have to be found in the exothermic reactions like slow oxidations, possible physical influences like coupled effects of condensation and wetting (mainly adsorption) of water molecules and microbial processes, which are occurring in these large wood heaps at common ambient temperatures. Due to the poor heat conductive properties of the bulk material, the heat produced inside the pile could not dissipate to the surroundings completely. Thus, a positive heat feedback loop would be initiated, which would finally turn in an extensive fire.

Among the factors influencing the possibility and frequency of occurrence of self-ignition, one of the most important is the storage geometry, since the heat production occurs in the whole bulked volume and the heat is dissipated only through the pile surface. Therefore, Steen (2000) described that an increase of the volume to surface (V/A) ratio results in a smaller self-ignition temperature ($T_{SI}$). The $T_{SI}$ is defined as the highest surrounding temperature at which no ignition occurs: this means, for a surrounding temperature higher than the $T_{SI}$, the heat released by the reactions inside the material is larger than the heat transmission to the surroundings, making the process running into an ignition. The V/A dependence of the $T_{SI}$ leads to the possibility of self-ignition at normal ambient temperatures, if the amount of stored material is large enough.

Standard laboratory scale investigation of the self-ignition in accordance to the European standard DIN EN 15188 (2007) was

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**Nomenclature (SI units)**

| Quantity | Description, SI unit |
|---|---|
| $A$ | Area, [m$^2$] |
| $b$ | Biomass death rate constant, [s$^{-1}$] |
| $C_k$ | Concentration of the species $k$, [kg/m$^3$] |
| CD | Pre-exponential factor condensation/adsorption, [s$^{-1}$] |
| $c_p$ | Specific heat, [J/kg K] |
| $D_k$ | Diffusion coefficient of the gas species $k$, [m$^2$/s] |
| $E$ | Activation energy, [J/mol] |
| EV | Pre-exponential factor evaporation/desorption, [s$^{-1}$] |
| $f$ | Fraction of dead biomass converted to inert, [-] |
| $k_0$ | Pre-exponential factor, [s$^{-1}$] |
| $K_b$ | Substrate saturation constant for MB, [kg/m$^3$] |
| $K_h$ | Hydrolysis constant, [s$^{-1}$] |
| $K_{MH}$ | Saturation constant for the group MH/$X$, [-] |
| $M_k$ | Molecular weight of the species $k$, [kg/mol] |
| MB | Easy-biodegradable fraction concentration, [kg/m$^3$] |
| MH | Slowly-biodegradable fraction concentration, [kg/m$^3$] |
| $q_{O_2}$ | Oxycaloric coefficient, [J/kg] |
| $R$ | Gas Universal constant, [J/mol K] |
| $S_{C_k}$ | Conversion rate of the species $k$, [kg/m$^3$ s] |
| $S_T$ | Heat production, [W/m$^3$] |
| $S_v$ | Evaporation/desorption rate of liquid water, [kg/m$^3$ s] |
| $S_w$ | Condensation/adsorption rate of water vapor, [kg/m$^3$ s] |
| $t$ | Time, [s] |
| $T$ | Temperature, [K] |
| $V$ | Volume, [m$^3$] |
| $X$ | Biomass concentration, [kg/m$^3$] |
| $Y$ | Biomass yield on MB, [-] |
| $Y_{CO_2}$ | Biomass yield on $CO_2$, [-] |
| $\Delta H_R$ | Calorific value, [J/kg] |
| $\Delta H_v$ | Water evaporation enthalpy, [J/kg] |
| $\lambda$ | Thermal conductivity, [W/m K] |
| $\mu_m$ | Biomass growth rate constant, [s$^{-1}$] |
| $\nu_k$ | Stoichiometric coefficient of the species $k$, [-] |
| $\rho$ | Density, [kg/m$^3$] |

performed in this work. Even though these experiments are necessary to determine the $T_{SI}$ and the kinetic parameter of the combustion reaction, the extrapolation methods are valid only for simple defined geometries. Furthermore, hot storage experiments are usually performed at temperatures much higher than 100 °C, due to comparably small V/A ratios. Hence, the influences of moisture and of microbial processes on the course of self-ignition are reflected only in the initial phases of such experiments. Nevertheless, these aspects are important since moisture can increase the possibility of occurrence of a self-ignition, like shown by Lohrer, Schmidt, and Krause (2005) and affects the time to ignition, as already reported by Simms and Law (1967). In addition, a high microbial activity can bring important additional heat, see Weppen (2001).

In order to surmount these shortcomings, modeling of the coupled differential equations of heat and species transfer is needed. Therefore, a mathematical model has been developed to simulate the heating-up and possible self-ignition processes in wood storage. The model comprises three heat sources:

- A heat production rate, deriving from Arrhenius-type oxidation reactions inside the pile;
- A physical heat production/consumption rate, which reflects the transferred heat from endothermic evaporation/desorption and exothermic condensation/adsorption processes;
- A heat source arising from microbial processes, which is proportional to the oxygen consumption during aerobic respiration. In order to define proper oxygen consumption kinetics, respiratory experiments, coming from a modification of the so-called Sturm Test: ISO 14852 guideline (1999), have been performed.

The model has been solved numerically and has then been validated with laboratory experiments and finally compared to real scale experiments. For these experiments the temperature and concentrations of four different gases in two freshly established large pine wood piles have been measured.

This work presents experimental results of the hot storage tests as well as of the respiratory experiments and of the large scale measurements, which were used to generate the input parameter of the model. Furthermore, predictions of the developed model and comparison with experimental data are presented. This work aims for better understanding of the precursors of the self-ignition of large-scale wood piles and in achieving a safe and sustainable storage of this resource.

## 2. Experiment

### 2.1. Hot storage tests

The European standard DIN EN 15188 (2007) establishes that the so-called hot storage test should be used for the laboratory scale investigation of the self-ignition processes. In Fig. 1 the set-up of this test is schematically drawn: the specimen to study is exposed to high temperature surroundings and the temperature in its center is measured. At first, the temperature in the sample will reach the surrounding temperature. Subsequently, if the heat released inside the probe is greater than heat dissipation, the material will reach self-ignition. By varying the surrounding temperature, the minimum $T_{SI}$ and the induction time to self-ignition – i.e. the time from the beginning of the experiment to the exponential increase in the temperature – are determined. The experiments are repeated for samples with different V/A ratios: then the values of $T_{SI}$ and induction time to self-ignition ($t_{SI}$) can be extrapolated to bigger V/A ratios for the same geometry type, as shown in Figs. 2 and 3 for pine sawdust and pine wood chips. The two graphs show also that a reduction in the particle size increases the possibility of occurrence of a self-ignition, since both values of self-ignition temperature and of induction time to self-ignition are smaller for pine sawdust (average particle size 0.25 mm) than for pine wood chips (average particle size 10 mm).

### 2.2. Respirometric tests

In order to estimate the activity during the microbial respiration, experiments were performed at a laboratory scale. A schematic drawing of the experimental set-up, which comes from a modification of the ISO 14852 guideline (1999), is shown in Fig. 4.

In these experiments, the microbial activity is determined through the monitoring of the production of carbon dioxide, which under aerobic conditions is linked to the oxygen consumption. The heart of the set-up is a 4-L sealed glass recipient in which the substance to be incubated is inserted. The walls of the reactor are tempered, as to maintain the desired temperature, which is