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A Combustion Model of Vegetation Burning in "Tiger" Fire Propagation Tool

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Abstract. In this paper, we propose a semi-physical model for the burning of vegetation in a wildland fire. The main physical-chemical processes involved in fire spreading are modelled through a set of ordinary differential equations, which describe the combustion process as linearly related to the consumption of fuel. The water evaporation process from leaves and wood is also considered. Mass and energy balance equations are written for fuel (leaves and wood) assuming that combustion process is homogeneous in space. The model is developed with the final aim of simulating large-scale wildland fires which spread on heterogeneous landscape while keeping the computation cost very low.

INTRODUCTION

Computational combustion is a wide topic spanning through several scientific fields such as the engineering of gas turbines, industrial furnaces, combustion engines, nuclear power plants, and fire safety in buildings [1-3]. A search in SCOPUS for the terms "combustion AND (modeling OR simulation)" in article title and abstract returns 49,589 results. However, adding to the query the term "AND (wildfire OR 'forest fire'), i.e. free ranging fires due to the combustion of vegetation, only 257 documents are returned. Indeed, the numerical modeling of wildfires, one of the oldest combustion phenomena on Earth, is relatively underrepresented. Recently, advances in computational power have led to several physical models aiming at representing both the physics and chemistry of fire spread in a given vegetation, and the environmental conditions [4]. Some examples are FIRESTAR [5], FIRETEC [6], FIRELES [7] and Wildland Fire Dynamics Simulator [8]. However, these models use fine spatial scales, e.g. the biomass volume unit in FIRETEC is 20 cm3, and require very high computational resources, precluding their use as operationally oriented tools [4, 9]. On the opposite end of the spectrum, semi-physical models are computationally efficient [4] but suffer of uncertainty, imprecision, need calibration, and assume a condition of non-uniqueness , [5, 10]. A much known wild-land fire simulator is FARSITE, which is based on Rotheremel's model and uses available GIS data, and information about the fuel types and wind conditions in the area under study [11]. Another approach, successfully applied in real-world wild-land fires in heterogeneous environments, involves Cellular-Automata based models [12-16].

In this study, we present a new combustion model for fire spread prediction, with intermediate characteristics between semi-physical and physical models, allowing to balance pros- and-cons of both approaches.

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MATHEMATICAL FORMULATION OF COMBUSTION MODEL

The model describes dynamics of fuel (leaf and wood) consumption, moisture evaporation and energy balances for leaves and wood, using the following state variables: gas mass (G), leaf mass (L), diametric wood classes (W), leaf moisture (ML), wood moisture (MW), gas temperature (T_G), leaf temperature (T_L), wood temperature (T_W), leaf moisture temperature (T_{ML}), wood moisture temperature (T_{MW}). Given a time resolution of 1 minute, we assume that it is possible to consider T_L=T_{ML} and T_W = T_{MW} thus T_L is the temperature of both leaf and leaf moisture and TW is the temperature of both wood and wood moisture.

Leaf and wood combustion

The leaf and wood mass consumption rates are assumed to be proportional in time to their mass density according to the following equations:

$$\begin{aligned}\frac{dL}{dt} &= -\mathrm{k}_{\mathrm{ML}} \cdot r(T_L) \cdot L \\ \frac{dW}{dt} &= -\mathrm{k}_{\mathrm{MW}} \cdot r(T_W) \cdot \min(W, Exp_W)\end{aligned} \tag{1}$$

where k_{ML} and k_{MW} are parameters representing the effect of moisture on combustion, r(T_L) and r(T_W) are the leaf/wood reaction rates (modified Arrheneius law) and Exp_W is the exposed wood (simply calculated from the wood class diameter).

Moisture evaporation

In the simplified model, moisture levels represent at the same time internal and external water in leaves and wood. The evaporation is described by the following equations:

$$\begin{aligned}\frac{dML}{dt} &= -\mathrm{k}_{\mathrm{T_L}} \cdot ML \\ \frac{dMW}{dt} &= -\mathrm{k}_{\mathrm{T_W}} \cdot MW\end{aligned} \tag{2}$$

where k_{TL} and k_{TW} are the leaf and wood moisture evaporation parameters, simple linear functions of T_L and T_W. Finally, the gas mass density, which includes the air and the products of combustion and evaporation processes, is calculated from the global mass balance equation given by:

$$\frac{dG}{dt} = \frac{dL}{dt} + \frac{dML}{dt} + \frac{dW}{dt} + \frac{dMW}{dt}$$

Energy balances

Solid phases (L, W) exchange heat with Gas, produce heat by combustion processes, and lose heat by evaporation and irradiation. For simplicity we did not consider heat exchange between L and W.

$$\frac{dT_L}{dt} \cdot cs_L \cdot L = \left[A_L \cdot (T_G - T_L) \cdot (h_{L\_wind} + h_{L\_no\_wind}) \right] + \frac{dL}{dt} \cdot H_L - \frac{dML}{dt} \cdot \lambda_{L\_vap} - S_L \cdot \varepsilon_L \cdot \sigma \cdot (T_L^4 - T_\infty^4) \tag{3}$$

$$\frac{dT_W}{dt} \cdot cs_W \cdot W = \left[A_W \cdot (T_G - T_W) \cdot (h_{W\_wind} + h_{W\_no\_wind}) \right] + \frac{dW}{dt} \cdot H_W - \frac{dMW}{dt} \cdot \lambda_{W\_vap} - S_W \cdot \varepsilon_W \cdot \sigma \cdot (T_W^4 - T_\infty^4) \tag{4}$$

where cs_L is the weighted average of specific heats of L and ML, cs_W is the weighted average of specific heats of W and MW, HL is the leaf heat content, HW is the wood heat content.

In both equations, (3) and (4), the first term of the right hand side represents the heat exchange with gas with and without convection; the second term is the positive source due to the combustion phenomena; the third terms are the heat losses from the evaporation processes and finally, the last terms represent the heat losses for irradiation. In the model the energy balance of gas includes the heat exchanges with fuels and the irradiation process.

$$\begin{aligned}\frac{dT_G}{dt}\cdot cs_G\cdot G = &\left[A_L\cdot(h_{L\_wind}+h_{L\_no\_wind})\cdot(T_L\text{-}\mathrm{T}_G)+A_W\cdot(h_{W\_wind}+h_{W\_no\_wind})\cdot(T_W\text{-}\mathrm{T}_G)\right]+\\ &+\mathrm{S_L}\cdot\varepsilon_\mathrm{L}\cdot\sigma\cdot(T_\mathrm{L}^4\text{-}T_\infty^4)+\mathrm{S_W}\cdot\varepsilon_\mathrm{W}\cdot\sigma\cdot(T_\mathrm{W}^4\text{-}T_\infty^4)+\frac{dML}{dt}\cdot\lambda_{L\_vap}+\frac{dMW}{dt}\cdot\lambda_{W\_vap}\end{aligned} \quad (5)$$

where cs_G is the gas specific heat, A_L and A_W are the Leaf and Wood heat transfer surface areas, h_{L}*_wind* and h_{W}*_wind* are the Leaf and Wood heat transfer coefficients under windy conditions respectively, h_{L}*_no_wind* and h_{W}*_no_wind* are the Leaf and Wood heat transfer coefficients under non-windy conditions, SL and SW are the leaf and wood irradiation surface, ε_L and ε_W are the leaf and wood emissivity, σ is the Stephan Boltzaman constant, T_∞ is the environmental temperature (~300K), λ_{L_vap} and λ_{W_vap} are the leaf and wood heat of evaporation.

Also in the model are implemented the solid phases (L, W) heat exchanges with Gas, produce heat by combustion processes, and emit heat by evaporation and irradiation. For simplicity we did not consider heat exchange between L and W.

NUMERICAL SIMULATIONS

We analyzed the model behavior by numerical simulations. Figure 1 represents the evolution dynamics of biomass and temperature changes of wood and leaf: the graphs show that, after the ignition of leaf combustion, the temperature quickly rises up to 1200° C and then decreases, while wood combustion is much slower, and mainly determined by the type of the material and by the slow consumption of exposed wood.

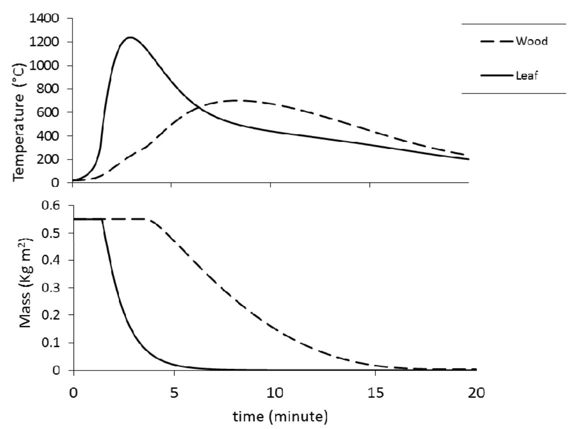

FIGURE 1. Temperature and mass dynamic of leaf and wood

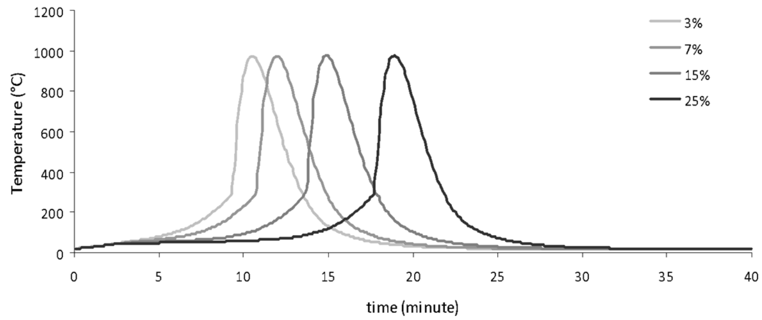

FIGURE 2. Temperature of leaf with four different moisture levels

In Figure 2 different temperature evolutions are reported for different initial moisture content in leaves. It appears clear that an increase in the moisture content delays the ignition of the biomass while the shape of the different curve remains unchanged, this is in agreement with experimental evidences that oxidation/combustion reactions of the solid fuel start in sequential order respect the drying processes of the biomass.

DISCUSSION AND CONCLUSIONS

The model is proposed as an intermediate between a coarse, semi-empirical approach and a chemistry- and physics-based combustion mode, and it is intended to be used with time scales typically associated to field measures. Results shows that our model give an acceptable precision using reasonable computational capacity.

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