CHEMICAL ENGINEERING TRANSACTIONS
VOL. 67, 2018
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Valerio Cozzani, Bruno Fabiano, Davide Manca

**ISBN** 978-88-95608-64-8; **ISSN** 2283-9216

# A Minimal Model for the Vegetation Combustion in Wildfire Simulators

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In this paper a semi-physical model for the vegetation burning in wildland fire is proposed. The model is developed with the final aim to simulate large scale wildland fires which spread on heterogeneous landscape. In a modular modelling approach, it can be seen as the cell model for a forest fire propagation tool to perform fast simulations for operational scope and fight fires interventions. It is constituted by a simple system of ordinary differential equations taking into account the main physico-chemical processes involved in the fire spreading while keeping the computation cost for simulations very low. Finally, the model is implemented in the modelling, at the intermediate scale (1 hectare), of the fire spreading in a homogeneous environment.

## 1. Introduction

Modelling the fire behavior in forests is a very challenging task, and, although there is an increasing literature on the subject, the numerical modeling of combustion phenomena in wildfires (one of the oldest combustion phenomena on Earth) is relatively underrepresented. The main problem which arises when dealing with the wildfire modelling is that the physical processes which are involved cover a very wide range of temporal and spatial scales. The fire spread is indeed a multi-physical phenomenon which involves scales that range from small scale of 1mm (ignition) to the landscape level (100 km).
As revealed by satellite maps (Caldarelli et al., 2001), fire patterns may exhibit irregular and even fractal shapes that are due to the local heterogeneous conditions (weather, fuel, and topography) encountered by the fire as it propagates. At the landscape level scale, the fire front is seen as a line separating the burned fuel from the virgin fuel, moving on a relief. However the essence of fire spread occurs at much more small scales where the heat transfer mechanisms, the thermal degradation, and the combustion take place. Moreover, it is at this level that the different local heterogeneities such as meteorology, topography and fuel interact with the fire front. There are different classifications of wildland models (Karplus, 1977; Pastor, 2003; Sullivan, 2007). The models developed at the smallest scale are combustion models (Grishin, 1987; Mell et al., 2007) which are based, for the most part, on a two-phase description of the flow with the fluid dynamics. Most of the basic phenomena that govern the emergence and spread of wildfire are generally considered at this scale: gas transport, turbulence, thermal degradation of the material, radiation exchange between the gas and the solid medium and in some cases the use of a detailed kinetics which include pyrolysis, combustion of volatile compounds and oxidation of condensed carbonaceous residue. A detailed model (Larini et al.,1998; Linn et al.,1997) thus requires the numerical solution of the balance equations of mass, energy and momentum for each phase and the radiative transfer equation. A realistic simulation therefore requires solving a system of equations involving tens of nonlinear partial and strongly coupled equations. 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 environmental conditions (Sullivan 2009). However, these models use fine spatial scales, e.g. the biomass volume unit in FIRETEC is 20 $cm^3$, and require very high

computational resources precluding their use as operationally oriented tools (Sullivan 2009, Guelpa et al. 2016). The resulting CPU time resolution limits applications to areas of small size, typically a few hundred meters in three directions. These detailed models must be considered as models of knowledge for understanding the behavior of the fire, to test alternative hypotheses or enrich the models, not suitable for simulating the spread of fire at the large scale (landscape level). On the opposite, empirical models are computational efficient (Sullivan 2009) but suffer of uncertainty and imprecision, calibration needs and the condition of non-uniqueness (Morvan and Dupuy 2004, Finney et al. 2013). Some examples are FIRESTAR (Morvan and Dupuy 2004), FIRETEC (Linn and Harlow 1997), FIRELES (Tachajapong et al. 2008) and Wildland Fire Dynamics Simulator (Mell et al. 2007). At the landascape level, propagation models are very efficient as in most of the case are able to perform predictions in a CPU time that is much lower than real time ( Russo et al. 2014; 2016a, 2016b, 2016c). For the propagation model, it is common to numerically treat the fire perimeter as a group of contiguous independent cells that can grow in number, which is described in literature as a raster implementation (Sullivan, 2007; Alexandridis et al. 2008, 2011a, 2011b). Propagation models may be based on Cellular Automata (Karafyllidis and Thanailakis, 1997), stochastic Montecarlo methods (Adou et al., 2010), elliptic expansion with Hyugens'principle (Sullivan 2007) or small world network (Graham, M and Matthai, 2003). However, such propagation tools make use of empirical or semi-empirical rules or sub-models which then can be tuned to match the experimental data derived in real accidents. The building of combustion models for fire spread prediction with intermediate characteristics between empirical and physical models would allow to balance pros-and-cons of both approaches. Following Sullivan's classification, the model developed here is quasi-physical since it does not attempt to represent all chemistry involved in fire spread but attempts only to represent the main physical phenomena. In this study, we propose a new model for the vegetation combustion which can be considered intermediate between the detailed chemical-physical and the empirical/semi-empirical ones. It takes into account the main physical phenomena which arise at the scale of 1 m and it may be considered the smallest scale (cell level) of modelling in a landscape level propagation model. Finally, the model is implemented in the modelling, at the intermediate scale (1 hectare), of the fire spreading in a homogeneous environment.

## 2. Model development

The model is developed considering the fuel combustion as a local source of heat while transport phenomena like convection, diffusion of heat, the long range irradiation and the effect of the wind are considered distributed in space (2D).

### 2.1 The semi-physical minimal model for the vegetation combustion

The model representing the vegetation combustion is constructed considering two different kinds of fuel type (leaves and wood), which have different consumption velocity and moisture content. We assume that the combustion process is linearly related to the consumption of the fuel while the linear constants depend nonlinearly from the temperature following an Arrhenius' expression. The water evaporation process from the leaves and wood is also considered. Mass and energy balance equations are written considering that the combustion process is homogeneous in the space within a unit cell. The order of magnitude of the unit cell where this hypothesis is considered valid is 1 $m^2$.

Thus, mass balance equations are written for the leaf density (L), diametric wood classes (W), moisture content both for leaves (ML) and for wood (MW), and for the gas (G) which is constituted by air and combustion products. For the time resolution model (1 minute) it is possible to consider $T_L=T_{ML}$ and $T_W=T_{MW}$ where $T_L$ is the temperature of both leaf and leaf moisture and $T_W$ is the temperature of both wood and wood moisture.

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

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

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).

The model assumes that moisture is mainly constituted by water and that the internal levels of moisture are equal to those at surface, both for leave and wood. The rates of evaporation of moisture from leave and wood are described by the following equations:

$$\frac{dML}{dt} = -\mathrm{k}_{T_{ML}} \cdot ML$$
$$\frac{dMW}{dt} = -k_{T_{MW}} \cdot MW \qquad (2)$$

where $k_{TL}$ and $k_{TW}$ are the leaf and wood moisture evaporation parameters, simple linear functions of $T_L$ and $T_W$, respectively.
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:

$$\frac{dG}{dt} = \frac{dL}{dt} + \frac{dML}{dt} + \frac{dW}{dt} + \frac{dMW}{dt} \qquad (3)$$

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

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

$$\frac{dT_W}{dt} \cdot cs_W \cdot W = \left[A_W \cdot (T_G - T_W) \cdot (h_{W\_wind} + h_{W\_no\_wind})\right] + \frac{dW}{dt} \cdot H_W - \frac{dMW}{dt} \cdot \lambda_{W\_vap} - S_W \cdot \varepsilon_W \cdot \sigma \cdot (T_W^4 - T_\infty^4) \qquad (5)$$

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, $H_L$ is the leaf heat content, $H_W$ is the wood heat content.
In both equations, (4) and (5), the first term of the right hand side represents 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.
The gas exchanges heat with leaves and wood, with and without convection. Irradiation and evaporation are both processes which increase the enthalpy of the gas. Thus the balance equations are the following:

$$\frac{dT_G}{dt} \cdot cs_G \cdot G = \left[A_L \cdot (h_{L\_wind} + h_{L\_no\_wind}) \cdot (T_L - \mathrm{T}_G) + A_W \cdot (h_{W\_wind} + h_{W\_no\_wind}) \cdot (T_W - \mathrm{T}_G)\right] +$$
$$+ \mathrm{S}_\mathrm{L} \cdot \varepsilon_\mathrm{L} \cdot \sigma \cdot (T_\mathrm{L}^4 - T_\infty^4) + \mathrm{S}_\mathrm{W} \cdot \varepsilon_\mathrm{W} \cdot \sigma \cdot (T_\mathrm{W}^4 - T_\infty^4) + \frac{dML}{dt} \cdot \lambda_{L\_vap} + \frac{dMW}{dt} \cdot \lambda_{W\_vap} \qquad (6)$$

$cs_G$ 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 in the convection case, respectively; $h_{L\_no\_wind}$ and $h_{W\_no\_wind}$ are the leaf and wood heat transfer coefficients in absence of convection; $S_L$ and $S_W$ are the leaf and wood irradiation surface; $\varepsilon_L$ and $\varepsilon_W$ are the leaf and wood emissivity; $\sigma$ is the Stephan Boltzman constant; $T_\infty$ is the environmental temperature (~300K); $\lambda_{L\_vap}$ and $\lambda_{W\_vap}$ are the leaf and wood heat of evaporation.

### 2.2 The spatial distributed model for the convection and the heat diffusion

The spatial distributed model is constructed considering the transport phenomena in the air/gas phase while the fuel combustion is considered concentrated in the space and it will affect the dynamics of the gas phase trough a heat source term. For simplicity, we will consider 2D model (XY plane). The vertical convection flows (Z axis) are assessed for each pixel (cell) on the basis of the temperature gradients between the cell volumes and the above atmosphere ("chimney" effect). This vertical mass flow is compensated by lateral movements proportional to the temperature gradients with neighbouring pixels (mass conservation and constant pressure hypothesis).
The convection/diffusion processes induced by temperature gradients, are integrated with the wind vectors field providing a resulting re-balancing of air temperature in the model domain.
Under these assumptions the model equations are the following:

$$\frac{\partial T}{\partial t} = -\nabla \cdot \left( v\left(P,T\right)T \right) + \nabla \left( \chi(P)T \right) - h(T)(T - T_{\infty}) + f(t,T) \tag{7}$$

where T(P,t) is the temperature scalar field and v(P,t) is the wind vector field, function of space and time, $\chi$(P) is diffusion term, h(T) is the vertical convection heat transfer and f(t,T) is the heat source due to combustion in the cell, which is calculated from the equations (1)-(6).
The functions $\chi$(P) and h(P, T) are inversely proportional to the air mass contained in the cell and they can play the role of adjustable parameters.
The in-plane convective term is responsible for the motion of the air temperature field along the lines of the wind vector field:

$$v(P,T) = v_0(P,T) + \Delta v(P,T) \tag{8}$$

The perturbation of the wind field is computed at each time step by considering the gradient of the vertical convection heat flux. This effect takes into account the creation of a wind field due to temperature gradients. The strength of this effect can be controlled by an adjustable parameter. The in-plane diffusive term takes into account the mixing between air in the cell and air coming from neighbour cells at different temperatures. The third term accounts for the heat flux arising from vertical air convection, which produces a temperature decrease due to the heat transfer from the cell to the upper level of air. The fourth term describes the heat source related to the cell, that is, the combustion which occurs within the single cell. It is a generic function of temperature, time and other parameters and can be interpreted as the pixel model of combustion.

## 3. Numerical results

### 3.1 Simulations and experimental validation of the vegetation combustion model

We first analysed the model behaviour with several numerical simulations to assess the ability of the model to give results which are in qualitative agreement with the main physical processes governing the fire in a forest. Figure 1 represents the evolution in time of temperature (Figure 1a) and wood and leaf biomass (Figure 1b). The ignition is simulated by imposing an external (ambient) temperature around 350 K, which is higher of the leaf and wood ignition temperature.

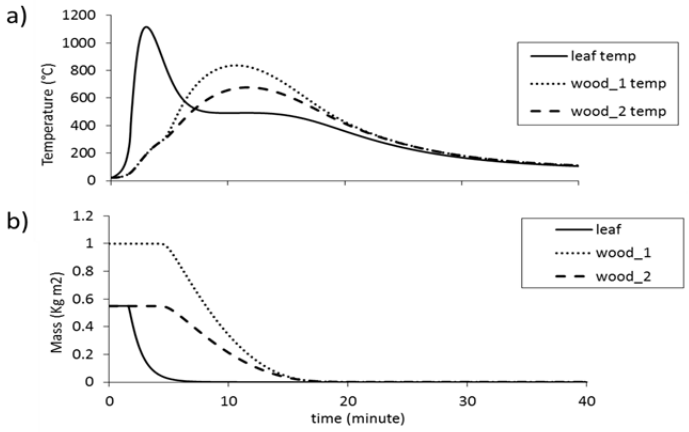


*Figure 1. Time evolution of temperature and biomass for leaf and two different wood species*

The graphs in Figure 1 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. Indeed, as it appears in Figure 1, different types of wood give different curves. The maximum temperature for different wood species is different according to the different heat content. This difference is also due to the different exposed wood which is specie-dependent and the different initial mass. Moreover, the model well predicts the different extinction time for the wood and leave, while different wood species consume more or less within the same time interval. In Figure 2 results from model simulations are compared with real data from experiments of fuel combustion. The experiments were performed in a burning tray in beds of Pinus pinaster needles and the temperature measurements were carried out by small towers of thermocouples.

More detail about the experimental set up can be found in (Mendes-Lopes et al. 2003). The model is calibrated using the external (ambient) temperature as fitting parameter and, using Nelder–Mead simplex algorithm. A very good agreement is obtained between the experimental data and the simulated curves ($R^2$ = 0.965, Figure 2).

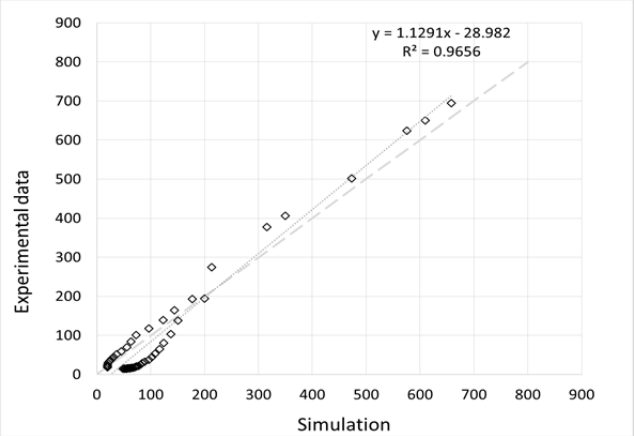


*Figure 2. A simulation vs experimental data of gas temperature around burning leaves : Leaf mass 1 kg $m^2$, leaf moisture 3%, ignition temperature 270°C.*

### 3.2 Simulations of the vegetation combustion model within the spatial distributed transport phenomena

The spatial distributed model has been simulated to test is ability to give physical reasonable results. The results of these simulations are reported in Figure 3, at different instant time ($t_1$, $t_2$, $t_{end}$) considering a homogeneous terrain of 1 hectare where the biomass of wood and leaves is distributed in two different portions of the plane.

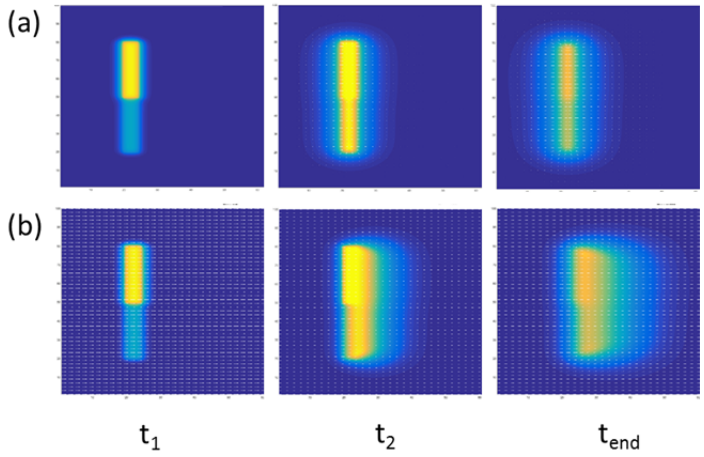


*Figure 3. Temperature contour plots in the (x,y) plane for tree different instants ($t_1$, $t_2$, $t_{end}$). a) no wind case, b) wind case*

These initial conditions are reported in the first column of Figure 3 (instant time $t_1$), where the yellow part corresponds to leaves and the light blue part is wood. In order to test wind effect, two scenarios were produced: a) with no wind and b) with wind traveling from left to right at 5 m/minute.
Coherently with the combustion model assumptions and consistently with results shown in Figure 3, leaf biomass (both in a and b cases) yields more heat, thus increasing the temperature, while wood biomass reach lower temperature values. Furthermore, after biomass consumption, leaf and wood biomass goes to zero ($t=t_{end}$). Finally, without atmospheric wind, heat is propagated symmetrically in both directions, while in case of wind heat is propagated more strongly in the wind direction.

## 4. Conclusions

A semi-physical model for the vegetation burning is proposed to simulate the essential characteristics of combustion phenomena for wildland fire modelling at landscape level. In spreading of forest wildland fires at landscape level, the level of complexity is very high as there are many chemo-physical processes evolving on different scales in space and time. Many are the phenomena interacting to give rise to the development of the fire front in an environment which is, in turn, characterized by heterogeneity in the space and stochasticity in time. Our model for the vegetation combustion is an intermediate between a coarse, semi-empirical approach and a chemistry- and physics-based combustion model, and it is intended to be used within the framework of model development for operational purpose. It consists of a set of ordinary differential equations which describes the main physical phenomena of the vegetation combustion while keeping the system equations very simple to allow fast calculations. In a modular modelling approach, the model can be thought as the core for the combustion processes inside a propagation tool for the landscape level modeling of the fire spreading. Results show that our model gives acceptable results consistent with physical observation and experimental results using reasonable computational capacity. The model has also been implemented to perform simulation at intermediate scale (1 hectare) by coupling it with a partial differential equation describing heat transport phenomena in a homogeneous environment with a very low computational cost. The numerical results show that the model is able to simulate the fire front development as well as to describe physical phenomena like the “chimney effect”.
Future work will be devoted to compare the numerical results with experimental data for medium scale for homogeneous environment and to include the ODE model for the vegetation burning in propagation model (e.g. cellular automata) to simulate real accident at landscape level.

**Acknowledgments**

Lucia Russo would like to thank Marco Imparato for his technical support.

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