PHYSICAL MODEL FOR SURFACE FOREST FIRE PREDICITIONS IN AMAZONIA

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Abstract
Wildland fires are a continuous occurring threat to people and properties in many places around the world. Many institutions in the United States, Europe and Australia are carrying out studies to understand and predict the behavior of such events support by advanced computer models. Forest fire understanding constitutes one of the most complex physical phenomena recently studied. The problem involves strong interaction of different physical and chemical processes like, turbulence, combustion, heat transfer, degradation of the condensed phase (biomass) among others. All these processes take place over a wide range of temporal and spatial scales, thus making modeling efforts even more challenging. Building such a physical model starts after identifying the governing processes, followed by the formulation of mathematical equations that better describe them with the expected accuracy. To the authors' knowledge, there is no study on physical modeling of surface fire propagation in rain forest type of vegetation. In this work we present a novel model for the predicition of unde-story fire propagation. Some preliminary results of simulations are discussed. Also, the paper present some laboratory scale fire experiments conducted near a fire site located in the State of Acre (Brazilian Rain Forest). Predictions have shown that at this premlimnary stage the proposed model is already able to capture the main effects of a surface forest fire typical of tropical regions.

Introduction
Historically, the action of man over nature was always very intense, especially in open and coastal areas, drawing the wealth of the savannas, pampas, and to a lesser intensity, mountainous areas. Tropical rainforests stay long on the fringes of these changes. However, population growth and the relentless pursuit of the countries to increase agricultural frontiers to accommodate increasing population groups, without adequate environmental planning of the use of these resources began to significantly alter the natural ecosystems in Brazil and worldwide. Large areas of wilderness are gradually being replaced by pastures and plantations [1].

The fire has been an important tool for the exploration and occupation of virgin lands in Brazil. However, after the second half of the twentieth century (1970), when agricultural expansion advanced toward the Midwest and North, fire has been applied more intensively. This type of land preparation (agricultural management) is used mainly on account of its simplicity, reliability and lower costs. The intensity and indiscriminate use of fire as a means of land cleaning areas for agriculture has become a serious environmental problem for the country. Also, large areas of pasture make use of fire for land management. In addition, the fast growth of sugar cane industry, led by the National Alcohol Program, has also add emissions of greenhouse gases following fire practices in this agricultural sector. By the early 1990's nearly four million hectares were burned, mainly in the Southeast and Northeast

regions of the country. These fires, combined with forest fires became a national concern because of increased gas and particulate emissions [2].

Different tools for the prediction of the rate of spread of wildland fires are being proposed by institutions in the United States, Canada, Australia and Europe. These tools are based on empirical, semi-empirical or physical models. These efforts, however, concentrate on ecosystems which largely differ from that found in the Amazon rainforest. An extensive literature review showed almost total absence of field and laboratory data on surface fire propagation in the Brazilian Rain Forest. As for numerical tools, the subject has never been addressed in Brazil.

It is very difficult, if not prohibitive, to study forest fires in large-scale repeatable field experiments, due to cost safety implications and to the adverse effects in local climate, terrain and vegetation. Still, there is a great need to improve our understanding of these events [4].

The threshold conditions for fire spread and the characteristics of fire in the tropical forests of the Brazilian Amazon are important determinants of fire effects on the ecosystem and biogeochemical cycle. Besides those which are intentionally set, accidental fires cause almost one-half of the burned area in the Amazon forest of Brazil. Often, they are associated to fires that start in adjacent areas cleared for agriculture or transportation corridors. Deforestation for land use change continues at a rate between 13 to 18 thousand square kilometers per year in Brazil (INPE, Monitoring of the Brazilian forest by satellite, 1998-2000, data available from INPE's web server http://www.inpe.br/Informacoes-Eventos/amazonia.htm). As a consequence it has been observed an increase in fragmented forest areas which provides an extensive interface between the remaining forest and the land cleared for agriculture and rangeland exploitation. The forest on this interface suffers drastic changes in micro weather, vegetation composition and structure, and ecological processes. Resilience of the forest is negatively altered turning it more favorable for sustaining combustion under the forest canopies after a prolonged drought period.

This work describes a novel mathematical model for the prediction of under-story fire propagation in tropical ecosystems. The paper presents some laboratory scale fire experiments conducted near a fire site located in the State of Acre (Brazilian Rain Forest). Figure 1 shows a typical tropical under-story material and a small flame initiating surface fire propagation.

Figure 1. Tropical under-story substrate and fire spreading.

The physical model set of equations

The primary task in building a physical model is the identification of its governing processes. This is then followed by the formulation of mathematical equations that better describe these processes in a way they can be solved to a desirable accuracy. Capturing the relevant processes at the time and length scales involved in surface forest fire is a very difficult task [11].

At the moment, the main objective is to develop a three-dimensional, fully transient model to predict surface fire spread in tropical ecosystems. For that the model has to be applied to the condensed phase (litter layer) as well as to the gas phase (surrounding air). Litter was considered a porous medium. The main processes taking place in this region are: drying, pyrolysis and glowing combustion. Heat transfer by radiation, convection and conduction as well as turbulent gas flow in the porous medium was also considered. In the gas phase (surrounding air) flame combustion takes place in a turbulent environment, where heat transfer to the porous medium by radiation and convection play a significant role.

To incorporate radiation from combusting gases, the physical model employs the discrete ordinates (DO) method, which solves the radiation transfer equation as a transport equation for a finite number of discrete solid angles, which can be used over a wide range of optical thicknesses, in participating media and for surface exchange.

The combustion submodel, necessary to track gas phase combustion, was based on a single step reaction for methane (CH4). Depending on the wind velocity, two modes of fire propagation are expected: plume-dominated fires and wind-driven fires, dominated by radiation and convection heat transfer, respectively. Without wind, the propagation of a fire through a forest fuel is governed by radiation heat transfer from the embers and flames. With wind, the fire propagates by convective heat transfer between the hot gases coming from the combustion zone and the solid fuel particles that undergo glowing combustion. In a plume-dominated fire, the flame is nearly vertical and fresh air is aspirated ahead of the fire front thereby cooling the solid fuel. For wind-driven fires, recirculation of hot gases through the unburned solid fuel, induces ignition of secondary fire fronts and accelerates fire propagation. To include the effects of turbulent flow it is used the RANS k-ε method.

The two main regions exchange mass, momentum, and energy. The behavior of the gas mixture resulting from the thermal degradation of the condensed phase and the combustion reactions is governed by the generalized Navier–Stokes equations. The set of equations are formulated in partial differential form. Some are non-linear, which does not favor analytical solutions. The system then must be solved by numerical methods. By their nature, differential equations are continuous and thus can be discretised. Finite volume (FV) was choosed as the discretisation method. The solution domain was divided into a regular grid of nodes.

The set of equations describing the proposed physical model are:

For the gas phase:

$$\frac{\partial}{\partial t}(\bar{\rho}) + \frac{\partial}{\partial x_j}(\rho\widetilde{u_j}) = \overline{\sum_{\alpha} \dot{M}_{s,\alpha}} \tag{1}$$

$$\frac{\partial}{\partial t}(\bar{\rho}\widetilde{u_i}) + \frac{\partial}{\partial x_j}(\bar{\rho}\widetilde{u_j}\widetilde{u_i}) = \overline{\frac{\partial}{\partial x_j}(\alpha_g \sigma_{ij})} + \bar{\rho} g_i \tag{2}$$

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{h}) + \frac{\partial}{\partial x_j}(\rho\widetilde{u_j}\bar{h}) = \overline{\frac{\partial}{\partial x_j}\left(\frac{\mu}{P_r}\frac{\partial T}{\partial x_j}\right)} - \overline{Q_{conv}} + \overline{\frac{\partial \alpha_g p}{\partial t}} + \overline{\alpha_g \sigma_g (J - 4\sigma T^4)} + \overline{\sum_{\alpha} \dot{M}_{s,\alpha}\, h_{s,\alpha}} \tag{3}$$

$$J = \int_0^{4\pi} I d\Omega \tag{4}$$

$$\frac{\partial}{\partial t}\left(\bar{\rho}\widetilde{Y_\alpha}\right) + \frac{\partial}{\partial x_j}\left(\rho\widetilde{u_j}\widetilde{Y_\alpha}\right) = \overline{\frac{\partial}{\partial x_j}\left(\frac{\mu}{P_r}\frac{\partial Y_\alpha}{\partial x_j}\right)} + \overline{\dot{w}_\alpha} + \overline{\dot{M}_{s,\alpha}} \tag{5}$$

$$Q_{conv} = h_{conv}\alpha_s\sigma_s(T - T_s) \tag{6}$$

For the condensed phase:

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s Y_{s,i}\right) = -\dot{w}_{s,pyr} \tag{7}$$

$$\frac{\partial}{\partial t}(\alpha_s\rho_s) = -\sum_\alpha \dot{M}_{s,\alpha} = -\dot{w}_{s,pyr} \tag{8}$$

$$\alpha_s\rho_s C_{ps}\frac{\partial}{\partial t}(T_s) = \overline{Q_{conv}} - \sum_\alpha \dot{M}_{s,\alpha}\, h_{s,\alpha} \tag{9}$$

The combustion process in the gas mixture is described by a single global reaction $CH4 + 2O_2 \rightarrow CO_2 + 2H_2O$. The litter pyrolysis rate is calculated by[12]:

$$\dot{w}_{s,pyr} = \frac{Q_s}{\Delta h_{pyr}} \times \frac{T_s - 293}{400 - 293} \tag{10}$$

If 293 K ≤ Ts ≤ 400 K, where Q_s is the energy received by the vegetation and Δh_{pyr} = 0.418 x 10^6 J/kg is the latent heat of pyrolysis. The condensed phase was treated as a porous medium composed of biomass and gases.

Numerical Model

The set of equations shown above was implemented in a computational code based on the OpenFoam library. The equations are discretized using the Finite Volume Method. The pressure-velocity coupling is done with a PISO algorithm.

The domain size is given in Tab. 1, the cell size is given in Tab. 2 and the boundary conditions used in the simulation are given in Tab. 3. In this simulation, as a starting point, it was used a constant value for the convection heat transfer (5.0 W/m^{2}K) between the gas and the condensed phase. The computational domain is show in Fig. 2.

Table 1. Domain size.

Domain size	Value (xyz)
Domain	2.0 m x 2.0 m x 2.0 m
Gas Phase	2.0 m x 1.9 m x 2.0 m
Condensed Phase	2.0 m x 0.1 m x 2.0 m

Table 2. Cell size.

Cell points in x, y and z directions	60x60x1

Table 3. Boundary conditions.

Condition	Values
Wind	u_x = 3.0 m/s, u_y = u_y = 0.0 m/s
Temperature	T = 293 K

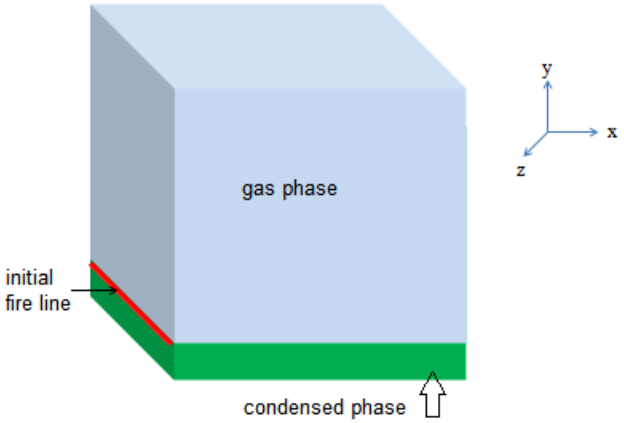

Figure 2. Computational domain.

As the combustion submodel is based on a single step reaction, it is necessary to impose a numerical ignition inside the domain. At the present calculations, this was achieved by imposing a temperature of the gaseous phase of 800K at a cube of 0.1m of side, as indicated at figure 2. Calculations have shown that the final results, once converged, do not depend on this initial temperature value.

The simulations were carried out on a single processor 1.46GHz with 4,2GiB. Typical processing time was 1 hour.

Results and Discussion

The results presented here are preliminary and obtained from the model described above. The simulation parameters are given in Tab. 4.

Table 4. Properties used in the model

Property	Value
S/V (surface area to volume ratio)	4000 [-]
α_g (volume fraction of the gas mixture)	0.7 [-]
α_s (volume fraction of the condensed phase)	0.3 [-]
Condensed phase thermal conductivity	0.12 [W/mK]
Condensed phase specific heat	1255 [J/kgK]
Condensed phase density	450 [kg/m^3]

Figure 3 shows the distribution of temperature in the condensed phase at the time t = 20s. The temperature field in the gas mixture for the time (t=20s) is shown in Fig. 4. It is worthy to mention that no initial CH_4 concentration was imposed at the beginning of the simulation. The fuel in the gas phase was a result of the pyrolysis at the condensed phase (vegetation). Therefore, the temperature rise shown at the Fig. 4 was solely given by the combustion reaction at the gaseous phase.

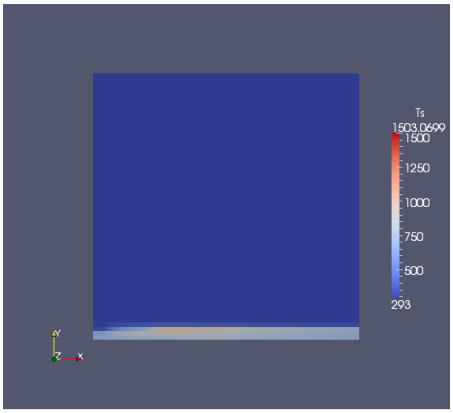

Figure 3. Temperature in the condensed phase at the time t=20s.

From the temperature fields in both condensed and gas phases, one can see that the fire front propagates from the left to the right as expected, since the wind is imposed at the left face of the computation domain.

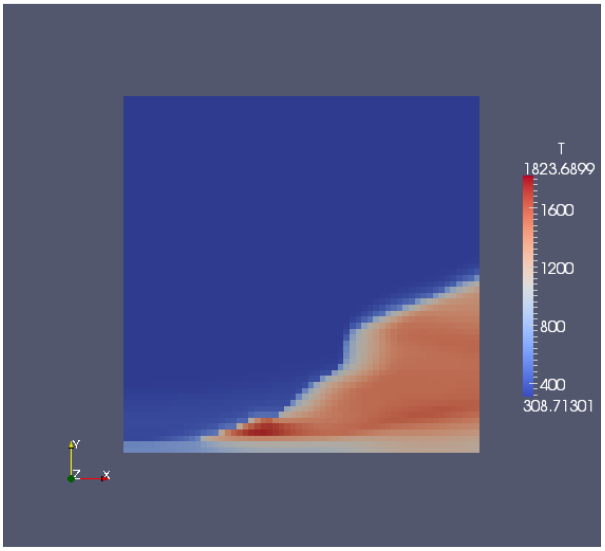

Figure 4. Temperature in the gas phase at the time t=20s

The velocity field of the gaseous phase is shown at the Fig. 5. One can see the increase of the velocity at the same region of higher temperature of the gaseous phase.

From the results above, it can be seen the fire propagation in the wind direction.

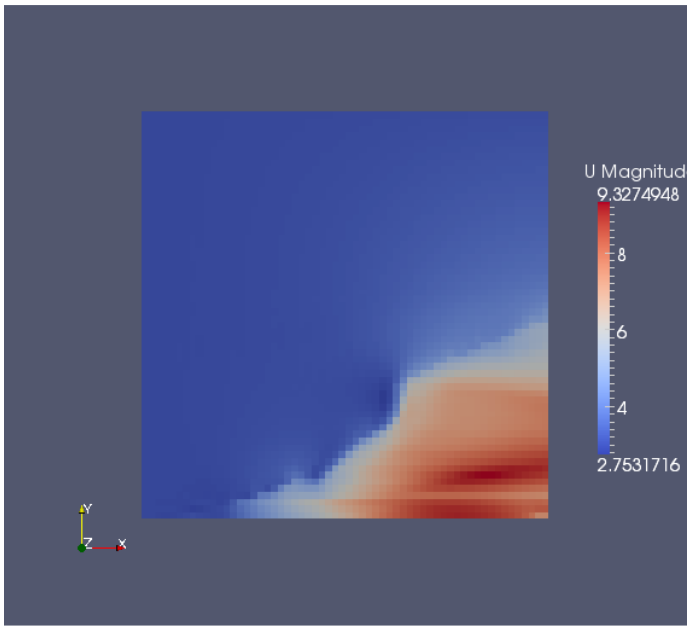

Figure 5. Velocity distribution at the gaseous phase at time t=20s

Field Experiments

In order to better understand the main processes observed in under-story ignition and fire spread a set of experiments was carried out near the fire site where the research group performed Amazonian deforestation fire studies. The litter material I the adjacent area of the main burning experiment was collected and transported to the nearby farm used as a research centre. In this farm the litter was spread in a grass field for drying. In another location the soil was cleaned and earthmoving for parallelism and flatness. A set of small iron sticks mark the central point and a 1.5 m circumference around it. Figure 6 shows a flame spreading following one experiment.

Litter was then collected, weighted and spread inside the marked circumference. Then, litter load, humidity and temperature were all measured prior to ignition. Wind speed and condensed phase temperatures were measured during the fire propagation. Temperature was checked by an infrared measurement system. Wind speed as measured by an anemometer, and the direction of it inferred thereafter.

Ignition took place in the center of the circumference by means of small amount of ethanol poured inside a 10 cm round area. In most of the experiments the mean velocity of propagation was between 0.11 and 0.20 m/min. These values are much less than those predicted by the proposed model. However, the litter load and geometric propagation were at different conditions. In the experiments it was clear the increase in flame spread velocity as the flame front enlarged. In the model, this flame front was set as an initial condition covering one side of the physical domain (2.0 m).

Figure 6. Laboratory fire spread experiment.

This model has shown to be adequate to describe the main effects of wildland surface fire propagation in the Amazonia Forest. The next step of this work will be the use of data gathered from a site visit to the forest.

Conclusions

A model to predict surface fire propagation in tropical ecosystem was presented. The model, in spite of its recent development, was able to track some of the key processes observed in under-story fire propagation. Predictions from the model were close to that presented in reference [12], in which flame velocities were of the order of 17 m/min. Mean propagation velocities from tropical field experiments were not higher than 0,20 m/min. The model will pass through a revision as to include variable constitutive equations, improved description of the porous media and other main parameters, for expanded and better predicitions.

Nomenclature

The following nomenclature applies.

C_{ps}^{k}	specific heat of vegetation
g_i	gravity acceleration in the i direction
h	enthalpy of the gas mixture
h_{conv}	gas mixture /vegetation heat-transfer coefficient
I	radiative intensity
J	irradiance
$\dot{M}_{s,\alpha}$	production of species α due to the decomposition of vegetation by pyrolysis
p	pressure of the gas mixture
P_r	Prandtl number
Q_{conv}	gas mixture /vegetation convective heat transfer
Q_{rad}	gas mixture /vegetation radiative heat transfer
t	time

x_j Cartesian coordinate in the *j* direction
T temperature of the gas mixture
T_s temperature of the vegetationT_s
u_j velocity in the *j* direction
Y_α mass fraction of species α
$Y_{s,i}$ mass fraction of dry vegetation

Greek symbols
α_g volume fraction of the gas mixture
α_s volume fraction of the vegetation
μ viscosity of the gas mixture
ρ density of the gas mixture
ρ_s density of the vegetation
σ Stefan-Boltzmann constant
σ_g absortion coefficient of the gas mixture
σ_{ij} stress tensor
σ_s surface area / volume ratio of vegetation
$\dot{w}_\alpha$ rate of production or destruction of species α due to combustion
$\dot{w}_{s,pyr}$ pyrolysis reaction rate

Subscripts
conv convection
g gas
pyr pyrolysis
rad radiation
s solid
α specie

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