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Validation of the Small World Network Model on a prescribed burning

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Abstract

This work aims to validate the Small World Network Model by comparing the numerical predicted rate of spread results to those obtained from a prescribed burning in the city of Oran in Algeria using Pinus Halepensis needles. In the first part of the experimental tests pine needles partially dried using microwave oven and climatic chamber were used. Fire propagation tests were then realized at different fuel moisture contents. In the second part of the tests, dead Pinus Halepensis needles were used in order to evaluate the effect of the terrain slope on fire spread. This model may be used to simulate the fire patterns both in homogeneous and heterogeneous landscapes. This model takes into account both the deterministic effects induced by the flame, and the probabilistic long range effects due to the spotting process of firebrands. Therefore, it combines as well the advantages of network models and those of macroscopic semi-physical models.

1. Introduction

Forest fires are very complex to model because of the number of intricate factors that can influence their propagation, and their multi-scale nature. Indeed, the characterization of their behavior depends on several parameters such as the fuel moisture content and the inclination of the terrain.

The small world model was proposed for the first time in 1998 by Watts and Strogatz in order to describe social behavior (Watts D. J. and Strogatz S. H., 1998). It is characterized by a high clustering coefficient and its ability to include randomly generated long-range connections. It was applied to model various phenomena such as epidemics, propagation of rumors (Zanette., 2002), the synchronization networks of cortical neurons (Yu Shan et al., 2008) etc.

On 2005, this model was successfully applied for the first time to forest fires within a collaboration between the two laboratories IUSTI (Polytech Marseille, France) and LEPM (USTO, Oran, Algeria) (Zekri et al., 2005). This variant of the small world model is based on two important requirements : it takes into account the flame radiation and the convection induced by the flame. In fact, the flame is modeled as having a cylindrical shape that emits a thermal radiation from its surface. Indeed, from each m² of the flame surface, N quanta of energy q are randomly generated using the statistical Monte Carlo method. In the other side, it considers the physics of combustion and the ignition and combustion properties of fine fuel elements which lead to the energy balance. The Small World Model was previously validated for three cases studies: fire experiments conducted in South Africa in 1992 (Savanna fires), historical fires that occurred in Lançon (France) in 2005 (Adou et al., 2010), and the historical fire of Suartone in Corsica 2003 (Hamamousse et al., 2021). In this work, the most recent version of this model is used to compare the real and the numerical rate of spread at different fuel moisture contents (for partially dried samples) and different terrain slopes (for naturally fead fuel).

2. Small World Network Model overview

In this model, the fuel medium is preheated to ignition by wind-driven convective and radiative heat emitted by the fire front and loses, in turn, a fraction of this energy by radiation to its influence area.

Each fuel element has a cylindrical shape with a height *H* and a diameter *D*, and only a top layer of thickness δ corresponding to the mean free path of radiation through the considered combustible that can be related to its surface-to-volume ratio, $\boldsymbol{\sigma_k = \frac{S_k}{V_k}}$, and to the volume fraction of the solid phase, $\boldsymbol{\alpha_k = \frac{V_k}{V}}$, as $\boldsymbol{\delta = 4/\sigma_k \alpha_k}$ (De Mestre et al., 1989), and volume $\boldsymbol{V = \pi D^2 \delta}$ of this combustible is affected in the pre-heating process. Above this penetration length $\boldsymbol{\delta}$, it is supposed that the radiation do not interact with fuel elements. These latter are considered as having the same geometric and thermo-physical properties. We assume also that the wet and dry fine fuel elements absorptivities are equal ($\boldsymbol{a_{WFF} = a_{DFF}}$), and that their volume fraction $\boldsymbol{\alpha}$ and surface-to-volume ratio $\boldsymbol{\sigma}$ are not affected during the thermal degradation process, which implies that $\boldsymbol{\alpha_{WFF} = \alpha_{DFF}}$ and $\boldsymbol{\sigma_{WFF} = \sigma_{DFF}}$.

Following the Koo et al. model (Koo et al., 2005), the receptive vegetation cell is heated in three steps: First, its temperature is raised by the absorbed heat up to the boiling temperature of water, namely 373 K. Then, it stagnates until the moisture content of this combustible is evaporated. Hence, in this desiccation phase, the wet fine fuel (WFF) is dried by the evaporation process turning into a dried fine fuel (DFF). Finally, the temperature of the dried vegetation restarts to increase steadily until it attains the pyrolysis temperature. If the emitted quantity of VOC is sufficient, the ignition process occurs, marking the end of the endothermic phase of this cell. The energy conservation in a receptive cell $\boldsymbol{j}$ exposed to a fire ($\boldsymbol{N_{bc}}$ burning cells) yields to the following equations.

For a temperature below the boiling temperature of water ($\boldsymbol{T(j) < 373K}$), we have:

$$\sum_{i=1}^{N_{bc}}\left[q^+_{rad,fl}(i) + q^+_{rad,e}(i) + q^+_{conv}(i)\right] - q^-_{rad}(j) = \rho_{WFF}\, c_{p_{WFF}}\, \alpha_k \frac{dT(j)}{dt} \quad (1)$$

$\boldsymbol{q^+_{rad,fl}}$, $\boldsymbol{q^+_{rad,e}}$, $\boldsymbol{q^+_{conv}}$ and $\boldsymbol{q^-_{rad}}$ correspond respectively to the radiation of the flame, the radiation of embers, the convective preheating of the site located in the influence zone of the burning cell by the emitted hot gases and the radiative losses due to the heat transfer from the cell *j* to the ambient. $\boldsymbol{\rho_{WFF}}$ is the volumetric mass density of the wet fine fuel element and $\boldsymbol{c_{p_{WFF}}}$is its heat capacity.

When the temperature of the receptive cell is equal to $\boldsymbol{373K}$, the equation becomes:

$$\sum_{i=1}^{N_{bc}}\left[q^+_{rad,fl}(i) + q^+_{rad,e}(i) + q^+_{conv}(i)\right] - q^-_{rad}(j) = -\,\rho_{DFF}\, L_{vap}\, \alpha_k \frac{dm_c(j)}{dt} \quad (3)$$

The latent heat of water vaporization $\boldsymbol{L_{vap}}$ is equal to $\boldsymbol{.25 \times 10^6\ J/Kg}$.

Once the site temperature exceeds that of water evaporation ($\boldsymbol{373K < T(j) < T_{pyr}}$), we have:

$$\sum_{i=1}^{N_{bc}}\left[q^+_{rad,fl}(i) + q^+_{rad,e}(i) + q^+_{conv}(i)\right] - q^-_{rad}(j) = \rho_{DFF}\, \alpha_k \frac{dT(j)}{dt} \quad (4)$$

When it attains the pyrolysis temperature $\boldsymbol{T(j) = T_{pyr}}$, the conservation of energy implies:

$$\sum_{i=1}^{N_{bc}}\left[q^+_{rad,fl}(i) + q^+_{rad,e}(i) + q^+_{conv}(i)\right] - q^-_{rad}(j) = -\,\rho_{DFF}\, L_{pyr}\, \alpha_k \frac{dFPC}{dt} \quad (5)$$

FPC is the pyrolysis product content of the dry fuel and $\boldsymbol{L_{pyr}}$ is the latent heat of pyrolysis.

The figure bellow schematizes the flame spread, the energy transfer mechanisms and the control volume of the cell involved in preheating.

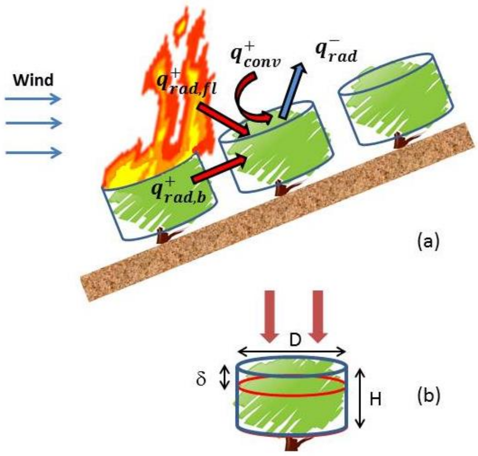

Figure 1: Flame spread schematic, with energy-transfer mechanisms indicated, and control volume of the cell involved in preheating.

We use a Monte Carlo method in order to estimate roughly the number of photons (quanta of energy) received by a healthy cell from the flame. This latter is modeled as a cylindrical solid body emitting radiation energy solely from its surface (solid flame model), this means that the properties of the flame such as its height, length, base diameter, angle and its emissive power are required. It is worth noting that the amount of energy received by a given cell depends on these flame properties, and may be affected by the air layer separating the flame and the cell, and the type of the vegetation cell. Moreover, some of these emitted quanta of energy may be absorbed by another burning cell situated between the emissive and the receptive sites. This screening effect that causes a loss of energy which does not contribute to the preheating of the healthy fuel is also taken into account by this MC method.

The radiated power is given by:

$$q^+_{rad,e}(i) = -a_{fm}\sigma\varepsilon_b T_b^4 \frac{d\tau}{dy} = a_{fm}\sigma\varepsilon_b T_b^4 \frac{1}{D_j}(exp(-d_1/\delta) - exp(-d_2/\delta)) \qquad (7)$$

Where σ is the Stefan-Boltzman constant (equal to $5.67 \times 10^{-8} Kg.s^{-3}.Kg^{-4}$), ε_b is the embers emissivity (it is assumed to be equal to one) and T_b is the temperature of the radiating embers. D_j corresponds to the diameter of the preheating site whose center is located at a distance $d_{ij} = d_1 + \frac{D_i+D_j}{2} = d_2 - \frac{D_i+D_j}{2}$ from the burning site.

The fuel cells situated in its influence area may be affected also by a wind-driven convective heat transfer mechanism which contributes to the heating of the receptive cell. If we suppose that the temperature difference decreases exponentially with the distance y as in (Pagni and Peterson., 1973). We can express this convective power as follows:

$$q^+_{conv}(i) = \frac{h}{\delta}(T_f - T_j)e^{-0.3 d_{ij}/L_f} \qquad (8)$$

We consider here that the length flame is approximately equal to one third of the characteristic length.
L_f is the flame length and T_f its temperature. h is an average heat transfer coefficient and is determined by the equation hereunder (Pagni and Peterson., 1973):

$$h = \frac{k_f}{d_{ij}} 0.037\, Re_{d_{ij}}^{0.8}\, Pr^{1/3} \qquad (9)$$

k_f and Pr are the thermal conductivity and the dimensionless Prandtl number

Hence, the combustible cell exposed to the flame gains energy by radiative (flame and embers radiations) and convective (heat transported by hot gases) processes. However, it loses also a part of this stored heat by radiating it to the surrounding environment. These radiative losses can be expressed as:

$$q_{rad}^{-}(j) = \frac{1}{\delta}\varepsilon_{fm}\sigma\left({T_j}^4 - {T_\infty}^4\right) \quad (10)$$

$\boldsymbol{\varepsilon_{fm}}$ is the fuel medium emissivity and $\boldsymbol{T_\infty}$ is the ambient temperature.

3. Validation of the Small world Network Model

In this work, the numerical rate of spread is compared to the experimental one :

- At different fuel moisture contents (for partially dried samples)
- At different terrain slopes (for naturally fead fuel).

The prescribed burning experiences were realized at the laboratory LEPM situated at the University of Sciences and Technology of Oran during spring 2021. 150 g masses of Pinus halepensis needles were homogeneously distributed on a metallic burning table of dimensions 88.5cm x 37.5cm. The fuel bed thickness and charge were about 1cm and 0.5kg/m², respectively. The fuel bed was divided into seven different positions (Figure 2); fire spread was then calculated by recording the time taken by the flame to pass between two successive positions.

Figure 2- Fire propagation table.

The first series of tests was realized on flat ground using pine needles dried partially using a microwave oven and a climatic chamber. The second series of tests was carried out according to different inclination angles (0, 5,9,13 and 17°) using naturally dried pine needles (dead needles) (figure 3).

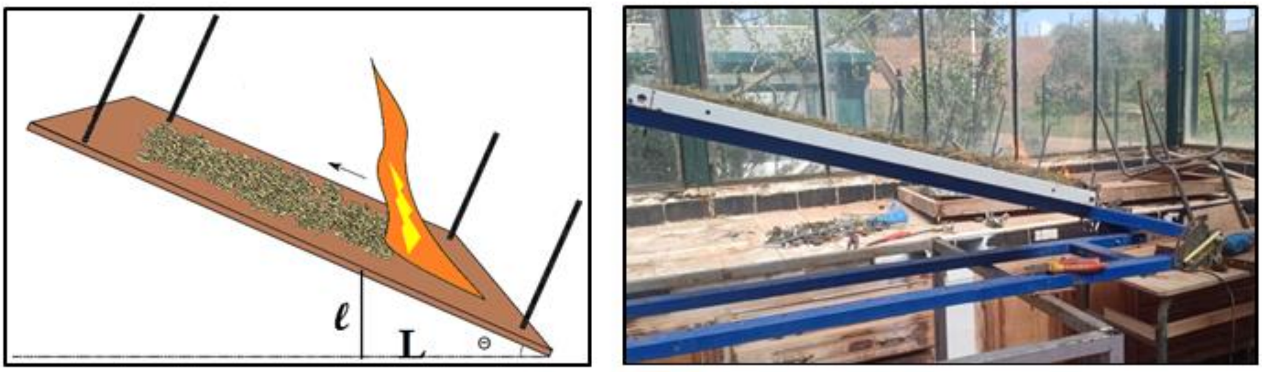

Figure 3- Inclined fire propagation table.

The study was divided into two main parts :

- Part 1 : The Network

2-dimentions network that contains homogeneous and uniform vegetation was constructed on a square based structure. The input data are occupancy, site radius, inclination, ignition type (punctual or linear).

- Part 2 : Fire propagation

The second part consists on the simulation of the fire propagation using the Small World Network Model. The network created in the previous section is integrated as an input of the Small World Network Model to simulate the fire propagation.

4. Results and discussions

In this section, we are going to present the experimental and the numerical results.

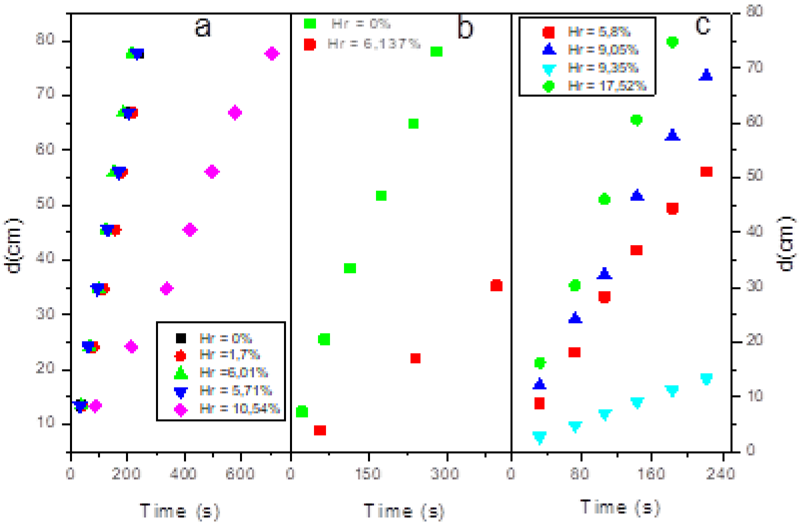

Figure 4- Fire spread evolution at different fuel moisture contents: Microwave oven , b) climatic chamber and c) naturally dead fuel.

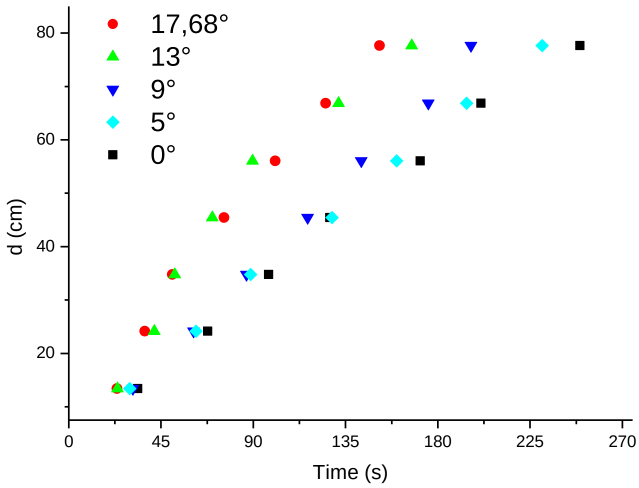

Figure 5- Fire spread at different table inclinations.

The comparison between the experimental and numerical results showed that the numerical simulations underestimate the fire rate of spread. This difference may be due to several reasons :

The intrinsic fuel parameters are not exactly estimated, some parameters differ from a region to another and from a season to another. Thus, it is important to characterize them experimentally.

The flame temperature captured by the thermocouples during the fire propagation indicates that the temperature decreases. This behavior is the same for low fuel moisture content.

5. Conclusion

The Small World Network model of fire propagation which combines the stochastic method of Monte Carlo and the semi-physicalapproach based on the resolution of the energy equation was validated on a prescribed burning realized at the laboratory LEPM situated at the University of Sciences and Technology of Oran during spring 2021. The comparison between the experimental and numerical results showed that the numerical simulations underestimate the fire rate of spread.

6. References

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