# Comparison between a semi-empirical and a physical model in predicting lab-scale fire rate of spread

**S. Vaccaro*, G. Battipaglia****
svaccaro@unisa.it
* Department of Civil Engineering University of Salerno. Italy
** Department of Industrial Engineering University of Salerno. Italy

**Abstract**
The rate of spread of fire (ROS) propagating across lab-scale domains has been evaluated through a semi-empirical and a physics based model designed to simulate fire propagation in forest environments. The study put in evidence the ability of the two models to provide reliable values of ROS under the effect of domain slope through the comparison with experimental findings from the literature.
The practical use of the two models has been discussed highlighting the different input data and operating approaches that must be used to perform a simulation. In particular, beside the physical specifics of the vegetative fuel (load, density, moisture content and surface to volume ratio), results indicated that also the parameters which module the fuel degradation processes play an important role.

## Introduction

Fire propagation rate across a real terrain depends on terrain shape and inclination, kind and distribution of fuel and environmental conditions. Different semi-empirical and empirical models, which considered wind and topographic slope as the main factors determining wildfires propagation rate, have been suggested [1-3]. Empirical models are based on data collected in specific geographic areas and their use is limited to conditions that closely resemble those used in the tests from which the model was derived. Semi-empirical models are based on energy conservation but do not distinguish between the different mechanisms of heat transfer [1]. Physical models are based on a simplified resolution of the conservation equations for mass, momentum, energy and chemical species and include also models that explicitly take into account the interaction between the gaseous phase and the fuel in order to model accurately the convective heat transfer [4,5]. Since based on physical principles, such models are potentially suitable to be applicable to a wider range of situations and conditions. However, their use is very limited since they are quite complex to manage and validated under very few experimental conditions.
Extensive reviews have been produced for the three types of models above [6,7], but a limited number of works dealt with comparisons between them [8-9]. The Rothermel's semi-empirical model, formulated in the 70's, is the precursors of the models of its kind, and is, currently, considered so notable for its good reliability to become a reference for later modelling developments [10,11]. On the other side,

WFDS, one of the recent physics-based models, appears to be one of the most promising [9]. A performance comparison between such two different approaches has never been carried out and the present work aims to assess their ability to reproduce the propagation of fires occurring on lab-scale domains and to put in evidence the main limits and advantages of both.

**Geometry definition and boundary conditions**

The fuel bed domain is 3 m long (x-direction) and 3 m wide (y-direction). The computational domain is 3.6 m long and 3.6 m wide. The size of the domain and the physical characteristics of the combustibles adopted in the simulations reproduced the experimental conditions of the works of Viegas [12] and Dupuy [13] who performed lab-scale tests considering, as fuel, needles of Pinus pinaster and Pinus halepensis, respectively. The parameters characterizing the vegetative fuel include the bulk density, defined as fuel load divided by its height, the moisture content on dry basis, the surface to volume ratio, the vegetation density and the char fraction. Different runs with the slope of the domain ($\alpha$) of 0°, 20°, 30° and 40° with respect to the horizontal plane were carried out.

**WFDS model and computational code**

The WFDS code, developed by NIST (National Institute of Standards and Technology) and the United States Forest Service is a specifically designed software to simulate forest fires. The physical model is based on a multiphase formulation of the conservation equations (mass, momentum, energy) and of the radiation transfer equation in a semi-transparent medium. The heterogeneous nature of the vegetation is described using a set of solid fuel families, each characterized by density of the dry material, moisture content and surface to volume ratio. LES calculation was employed to simulate the turbulent mixing of combustion gases with the surrounding.

To accomplish a correct description of the turbulent structures induced by the shearing effect above the fuel layer, the mesh division ($\delta$) in the gas phase above the fuel layer is imposed at least equal to the turbulence integral length scale, that is $\delta \leq$ fuel layer/4. Beside the definition of the physical parameters characterizing the vegetative species, WFDS includes two damping factors to module and limit the generation of fuel gas ($\sigma_p$) and water vapor ($\sigma_w$) due to the pyrolysis reaction and the dehydration, respectively. In the present work a sensitivity analysis of $\sigma_p$ and $\sigma_w$ values was performed in order to find their optimal values.

**The Rothermel model**

The Rothermel model [1] represents an authoritative reference for some current fire models such as FARSITE [11] and BEHAVE [10]. It estimates, through the eq. (1), the fire rate of spread (ROS) under steady state conditions, as the ratio between the heat flux the fuel receives from the source with respect to the heat required for it to be ignited.

$$\mathrm{ROS} = \frac{\mathrm{I_R}\xi\left(1+\varphi_w+\varphi_S\right)}{\rho_b \varepsilon Q_{ig}} \quad (1)$$

No information about the mechanisms of how heat is transferred is given. In equation (1) $I_R$ is the reaction intensity (kJ*min$^{-1}$*m$^{-2}$), $\xi$ is the propagating flux ratio, $\rho_b$ is the fuel bed bulk density (kg*m$^{-3}$), $\varepsilon$ is the effective heating number, and $Q_{ig}$ is the heat of pre-ignition (kJ*kg$^{-1}$). The reaction intensity depends on the fuel heat content, on the fuel packing ratio and on two damping factors related to the moisture and mineral contents. The propagation flux is a parameter dependent on the fuel surface to volume ratio and on the packing ratio. Contributions due to wind and slope appears in the eq. (1) as additional terms evaluated as proportional to $I_R\xi/(\rho_b\varepsilon Q_{ig})$. The coefficients $\varphi_w$ and $\varphi_s$ are dependent on the wind speed at the midflame height and on the slope of the domain, respectively. Model parameters are estimated by simple relationships, deduced from a large experimental data set gathered in the 70's. Environmental data, assumed constant, include wind velocity and slope of the domain. Inputs include common specifics related to the fuel such as load, humidity, height and surface to volume ratio. They also comprise data less easy to identify such as the fuel heat ($h$), the extinction moisture content ($m_s$), which represents the threshold water quantity beyond which fire extinction occurs, the total mineral content ($S_t$) and the effective mineral content ($S_e$), which is the amount of minerals able to negatively affect the decomposition rate. $h$, $S_t$, $S_e$ and $m_s$ data are not generally available in the literature, being parameters to be determined by experimental investigations. In the present work their values were taken from the work of Scott and Burgan [14] who assumed such parameters constant for a wide range of vegetative species.

**Results and Discussion**

The rate of spread (ROS) of the flames, defined as the rate of change of the distance run by the fire front, includes the possibility that the rate of spread may be time dependent even if the environmental conditions remain unchanged [12]. In Rothermel's model ROS is constant and it is just the output of the eq. (1). In the absence of wind, the ROS values, calculated by WFDS and by the Rothermel's model for the different domain inclinations, are reported in Figure 1 and 2, respectively along with the experimental results obtained by Viegas [12] and by Dupuy et al. [13]. The latter, who report also the error bar with a 95% confidence interval, found that the uncertainty in evaluating ROS increased at increasing slope angles. Results from the simulations indicated, in accordance with the experimental findings, an increasing trend of ROS with the terrain slope. Results calculated by WFDS (Fig. 1) overestimate the experimental values in correspondence of the intermediate values and underestimate them at the maximum value of $\alpha$. Actually, for $\alpha \geq 20°$, the predicted values fell within the confidence interval calculated by Dupuy et al. making such predicted values quite reliable. The Rothermel's model (Fig. 2), instead, well interpolates the Viegas results up to 30°, but fails in

predicting the fire behavior at 40° and at the experimental conditions adopted by Dupuy et al..

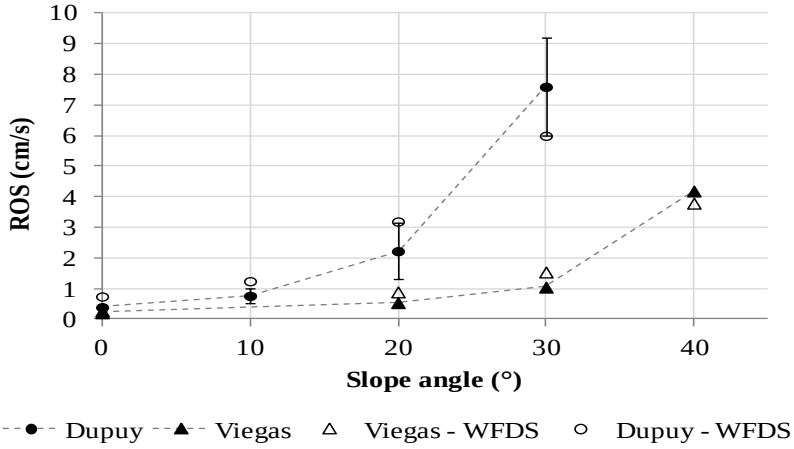


**Figure 1:** Comparison between the experimental and the WFDS results.

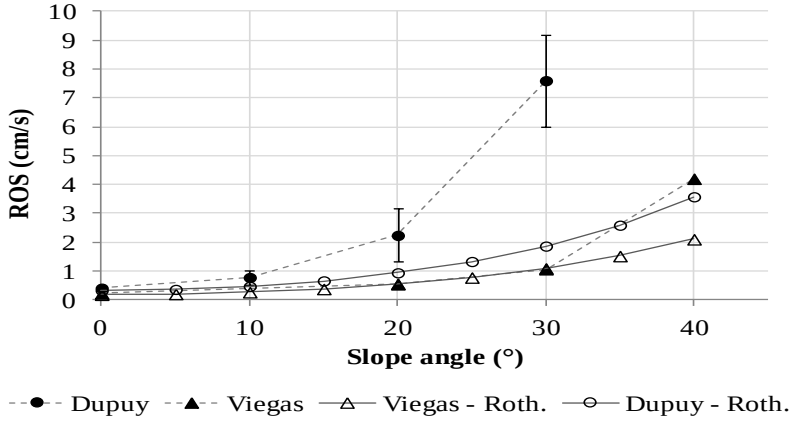


**Figure 2**: Comparison between the experimental and the Rothermel's model results.

A more quantitative evaluation of the ability of the two models to predict the actual fire behavior has been performed by plotting the calculated ($X_m$) and the experimental ($X_s$) ROS data sets as $X_m = k\ X_s$, where k is a proportionality constant ranging from 1 (identity condition) to 0. The calculated k values in the case of WFDS are 0.95 and 0.85 for experimental data set of Viegas and Dupuy, respectively while they are 0.53 and 0.26 in the case of the Rothermel's model indicating that WFDS is able to describe the actual fire behavior better than the Rotehrmel's model. It is worth noting, however, that the comparison between the

experimental results from Viegas, up to 30°, with the ROS values predicted by the Rothermel's model resulted in a k value equal to 1, showing in that range a perfect match.
The experimental results, reported in Figures 1 and 2, show how Viegas and Dupuy et al., in despite of the adoption of similar operative conditions, obtained quite different results. Viegas, operating with Pinus Pinaster needles, found that ROS increased by a factor almost 20 when the slope angle increased from 0° to 40°. Dupuy et al., instead, using Pinus halepensis needles as fuel, observed the same variation of ROS when the slope angle increased from 0° to 30°.
The disagreements on the absolute values obtained by the authors might be ascribed to the different physical characteristics of the fuels. Specifically, with respect to Viegas, Dupuy et al. operated with an higher fuel load (1.0 kg/m$^2$ vs 0.7 kg/m$^2$ on dry basis), considered pine needles with a lower moisture content (6.2% vs about 10.0%) and, more important, with an higher surface-to-volume ratio (about 7000 vs 4000). However, the introduction of the physical parameters of the two fuels in the Rothermel's model did not produce the same strong variation in the ROS values as found in the experimental investigations. On the contrary, with the same input values, WFDS was able to describe more closely such a marked difference between the two ROS trends. Such a difference in the two models output may be ascribed to a different evaluation of the damping factors that modulates the degradation process of the fuels. Specifically, in the Rothermel's model such factors are related to the extinction moisture and to the effective mineral contents, which govern the moisture and the mineral damping factors, respectively. The values of these parameters are not known and they were considered identical and constant in both fuels. On the contrary, in WFDS the damping factors, related to the dehydration and pyrolysis steps, were optimized to fit the experimental data. This means that the physical characteristics of the fuels are not generally sufficient to describe their degradation process being the correct evaluation of their degradation parameters also determinant. According to this point, the definition of the damping factors in WFDS gives the possibility to characterize the degradation features of a given fuel by affecting directly the related kinetic expressions and is not limited, therefore, to the identification of particular fuel composition items as in the Rothermel's model.

**Conclusions**

A simulation study of fires spreading across flat and inclined lab scale domain was performed using the physics-based code WFDS and the semi-empirical Rothermel's model. Results of simulations showed that only the first one was able to predict quite accurately the fire rate of spread of both the experimental data sets considered as reference. This was probably due to the possibility to better characterize the fuel by specifying not only its physical parameters, but also its degradation kinetics by the optimization of user-defined damping factors, which module the fuel dehydration and pyrolisys phenomena.

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