A FULLY PHYSICAL MODEL TO SIMULATE WILDFIRE BEHAVIOUR

Morvan Dominique
Université de la Méditerranée UNIMECA
Technopôle de Château Gombert 60 rue Joliot Curie
13453 Marseille cedex 13 France
dominique.morvan@univmed.fr

ABSTRACT

Some numerical results obtained using a fully physical model to simulate the behaviour of wildland fires are presented in this paper. The present model has been developed during previous European projects from the 4th and the 5th framework program (EFAISTOS, FIRESTAR). The model is based on a multi-phase formulation including the equations of conservation (mass, momentum, energy …) governing the evolution of the coupled system formed by the vegetation and the surrounding atmosphere.

INTRODUCTION

We know that global climate changes will modify fires regime in many ecosystems around the world. The recent catastrophic fires seasons observed last years in Mediterranean regions showed the necessity to promote new practices to manage the natural areas, especially those located near cities, in the wildland/urban interface (WUI). One of the main reasons which has contributed to increase fire hazard in Mediterranean regions, is the accumulation of solid fuel resulting paradoxically from the systematic fire fighting policy. To reduce forest fire risks, it is absolutely necessary to reduce such fuel accumulation, using fuel reduction techniques such as fuel clearance or prescribed burning. Low intensity fires can be used to reduce fuel load in the forests (burning the understory vegetation). In some particular circumstances, fires can also be used to fight wildland fires (tactical fires). To optimise these techniques and to be sure that they have a very low impact on the environment, it is necessary to improve the knowledge concerning the behaviour of fires in various situations (surface fires, crown fires…). This is in this context that we have developed a fully physical approach to simulate the behaviour of wildland fires. This model is based on a multiphase formulation (Grishin, 1997; Morvan *et al* 2001), including the resolution of the equations of conservation governing the evolution of the coupled system formed by the vegetation and the surrounding atmosphere. The main physical mechanisms controlling the propagation of the fire front, have been taken into account: the degradation of the vegetation (drying, pyrolysis and charcoal combustion), the behaviour of the burning zone (turbulent flow, combustion, radiation heat transfer) and the interaction between the flame front and the vegetation (heat transfer by convection and radiation, drag effects). After a short description concerning the methodology used to solve some physical mechanisms in this model, some numerical results obtained for the propagation of fires through homogeneous (grassland) and heterogeneous (shrubland, boreal forest) fuels are presented and compared with experimental data from the literature.

PHYSICAL MODEL

Previous experimental investigations, showed that only thin particles ($\phi < 6$ mm) can contribute actively to the propagation of a fire front. Consequently, the vegetation has been represented in this study, as families of solid fuel particles, each one being characterized by a set of specific physical properties such as, the volume fraction, the density, the surface area to volume ratio, the moisture content. Experimental measurements (Grishin, 1997) showed that for a temperature T < 1000 K (conditions observed ahead of a fire front), the gas mixture, resulting from the decomposition by pyrolysis of wood samples, was mainly composed of CO and CO_2 (CH_4 and H_2 can be also produced, but for higher temperature conditions). We have calculated, the time evolution of the variables describing the state of the vegetation (composition, mass, temperature), solving the equations of conservation of mass and energy including the various contributions coming from the different mechanisms present during the decomposition of the vegetation (drying, pyrolysis, char combustion) and from the terms of interaction with the surrounding atmosphere (convective and radiation heat transfer).

The turbulence and the combustion in the gaseous phase were treated using the RNG-k-ε model coupled with the combustion model EDC (Eddy Dissipation Concept), assuming that the reaction rate was mainly limited by the time necessary for the mixing between the gaseous fuel (limited here to CO) and the oxidizer. The action of the vegetation upon the gas flow and the turbulence was taken into account, adding source terms in the momentum and transport equations governing the evolution of the turbulent kinetic energy (k) and its dissipation rate (ε). These additional terms represent the contributions of distributed drag forces induced by the solid fuel elements constituting the vegetation. A constant drag coefficient $C_D = 0.15$ (defined using the plant area density) has been used in the simulations (Patton *et al* 2003).

The radiation heat transfer, representing one of the most important mechanism for the propagation of the fire front, has been solved using the discrete ordinate method (DOM), decomposing the whole space in 40 directions (S8 approximation in 2D). The radiation transfer equation (RTE) solved for this problem, included also, on the right end side, the contributions coming from the radiation due to the mixture formed by the gas and the soot particles, and the radiation coming from the embers.

Despite the fact that the behaviour of a wildfire is characterized by 3D phenomena, the present study is limited to a 2D configuration (the 3D version is in development). For surface fires propagating through grasses or shrubs, it can be assumed that the main transfers are located in a plan defined by the vertical direction and the direction of propagation. Consequently, it is not so wrong, to consider that a 2D analysis can reflect the major phenomena observed in this kind of situation, especially if the fuel is quasi homogeneous and if the initial dimensions of the line fire are sufficiently large.

NUMERICAL RESULTS AND DISCUSSION

As a preliminary step, the predictions of the present model have been compared and validated for surface fires at small scale, using experimental data obtained for homogeneous solid fuel in a wind tunnel (IFSL in Missoula MT-USA) (Catchpole *et al*, 1998). The results reported in Figure 1 represent a comparison between the rate of spread (ROS) evaluated numerically from the time evolution of the position of the pyrolysis front in the solid fuel (corresponding to the isotherm T=500 K) and the experimental observations made in the fire wind tunnel. The calculations and the experimental fires were carried out for the same solid fuels (pine needles, excelsior, sticks), forming a dead fuel bed. Because all the interactions between the solid fuel and the surrounding atmosphere (including the burning zone) depend on the specific surface of the solid fuel/gas interface, the surface volume ration σ_S constitutes one of the most important physical parameter characterizing the fuel layer. This parameter was ranging here between 630 m^{-1} (pine sticks) and 7566 m^{-1} (regular excelsior). Considering the very non-linear nature of the physical phenomena present in this problem (the decomposition by pyrolysis of the solid fuel, the turbulent combustion in the flaming zone, the radiation heat transfer between the flaming zone and the solid fuel), we can consider that the comparison between the numerical predictions and the experimental data are in a quite good agreement. There is some situations for which the comparison is not so good, for pine sticks for example. In this case, we must notice that the size of the particles ($\phi \sim 6$ mm) exceeded the threshold value for which the thermally thin hypothesis (used to solve the heat balance equation in the solid phase) can be considered as valid. Then the calculations were extended to large scale fires propagating through an homogeneous grassland on a flat terrain. The main advantage of this configuration is the existence of a large number of experimental data collected during various experimental campaigns carried out in Australia and also from direct observations of wildfires (Cheney *et al*, 1998).

The calculations have been carried out on a 150 m long stand, using a set of physical parameters presenting the same characteristics than a grass found in Australia (*Themeda australis*):

Table 1: Physical properties of the solid fuel layer

Fuel depth (m)	0.7
Fuel volume fraction	0.002
Fuel density (kg/m^3)	500
Surface/Volume ratio (m^{-1})	4000
Fuel moisture content (%)	5%

A snapshot of the temperature and the velocity fields calculated for two wind speeds U_W = 3 m/s (on top) and 5 m/s (on bottom), is shown in Figure 2. For U_W equal to 3 m/s, we observe that the flow field around the fire front is strongly affected by the fire itself. In some manner, the fire front generate its own flow independently from the inlet wind flow. For U_W equal to 5 m/s, despite these moderate wind conditions, we notice that the flame and the plume are notably deviated by the wind flow. As this is currently observed for pool fire, the animations (not seen here), highlighted also the formation of puffing instabilities (inducing vertical oscillations of the flame) resulting from the development of a thermo-convective instability between the burning zone and the surrounding fresh gases. The evolution of the rate of spread (ROS) as a function of the 10 m open wind speed (U_W) is represented in Figure 3 and compared with experimental data obtained from experimental fires in grasslands (Cheney *et al*, 1998) and direct observations of uncontrolled wildfires. To complete the comparison, we have also added some results obtained in 3D using the code *FIRETEC* developed at the Los Alamos National Laboratory (Linn *et al*, 2005), and the predictions of the operational tools Mk5 and BEHAVE currently used respectively, in Australia and in USA. From a general point of view, the numerical predictions obtained in the present study in 2D are in relative good agreement with the data of the literature. Both experimental data and numerical results, show the same behaviour: a quasi-linear dependence between the ROS and U_W for moderate wind conditions and a sharp increase of the ROS for stronger wind conditions. The same remark can be made for the fire line intensity (represented in Figure 4), defined as follows:

$$I = \Delta H_C \times m \qquad (1)$$

where ΔH_C (kJ/kg) and m designs the heat of combustion of wood and the mass loss rate (kg/m.s), respectively. We remark that, even for relatively low wind conditions, the fire line intensities are always very high, often larger than 7000 kW/m which represents the empirical critical threshold separating a weak and an intense fire behaviour (needing the use of aerial means to fight the fire). For heterogeneous fuel layers such as those observed in a Mediterranean garrigue and maquis (shrublands) (Morvan *et al*, 2004), the increase of the biomass near the ground enhances the interaction between the wind flow and the vegetation. Shear flow instabilities (combine with thermo-convetive instabilities always present in the plume) induce the re-circulation of hot gases inside the vegetation strata, ahead of the fire front, contributing to an enhancement of the convective heat transfer with the unburned vegetation (see Figure 5). As a function of the intensity of the wind and of the accumulation of the biomass, both plume dominated fires (piloted by radiation heat transfer) and wind driven fires (piloted by convection heat transfer) can be observed.

Then this approach has been generalised to simulate crown fires in similar conditions than the International Crown Fire Experiment (ICFME) performed in the North West territories in Canada (Stocks *et al*, 2004). In this case, the vegetation was structured in two fuel layers, representing the understory vegetation (composed by shrubs and small trees) and the canopy (see Figure 6 representing the vertical distribution of solid fuel density). In this case, we were interested to study the mechanisms governing the vertical transition of the fire, from the surface fuel to the canopy and the conditions (surface fuel load, wind speed) necessary to sustain the propagation of a crown fire. Both in the experiments and in the numerical simulations, the fire was ignited on the ground. The numerical results (see Figure 7 and 8) show that the intensity of the wind speed affects considerably the onset of the vertical transition of the fire from the understory vegetation to the canopy. For a wind speed U_W = 5 m/s, the propagation of the fire is limited to the surface fuel, the canopy is weakly affected by the fire as shown in Figure 8. This kind of behaviour is referenced in the literature as a passive crown fire or a torching. For a wind speed U_W = 10 m/s, the fire forms a continuous front from the surface fuel to the top of the canopy, all the available solid fuel is affected by the fire. This type of situation is referenced in the literature as an active crown fire. The numerical results show clearly that, in many cases, the behaviour (especially the rate of spread) of crown fires is mainly affected by the amount and the structure of the surface fuel. This phenomena is clearly shown in Figure 9, representing the ROS obtained for two surface fuel loads (0.225 and 2.25 kg/m^2) and for the wind speed U_W ranged between 5 and 30 m/s. The independent crown fire regime, corresponding to a propagation of the fire through the canopy independently from the existence or not of a surface fire, has never been observed in our simulations.

CONCLUSION

We can conclude that, in the future, the use of such physical model can be a good way to optimise fuel management techniques (such as the prescribed burning, the creation of fuel breaks) to reduce fire hazard especially in the wildland urban interface (WUI) or along railways or highways (Dupuy *et al*, 2005; Hanson *et al*, 2000). In the domain of risks and safety engineering, it constitutes also a good approach to evaluate the efficiency of some installations such the fuel breaks.

A part of the results (rate of spread, fire intensity) were compared with experimental data available in the literature and with predictions obtained using empirical operational tools (MkV, BEHAVE) used by fire fighters, and forests services. These comparisons showed that, in many cases, the predictions obtained using a semi-empirical model such as BEHAVE (which constitutes the more often operational tool used in the world) were not in good agreement with real observations on large scale fires. We can explain this discrepancy as follows: the data collected on small scale fires in laboratory (in a wind tunnel), used to close the energy balance, in the semi-empirical models, between the heat released by the fire and the heat flux absorbed by the unburned vegetation, cannot be extrapolated to understand the behaviour of a fire at large scale.

This remark constitutes a additional justification for the elaboration of a new generation of tools for the management of forest fires (monitoring, forecast), based on a more physical approach such as the model presented here.

At large scale, especially for crown fires in a forest, the present 2D approximation constitutes certainly a crude approach of the real phenomena which exhibit a 3D behaviour. This work is in progress in the frame work of the 6th European Union FireParadox project.

REFERENCES

Grishin, A.M., 1997, “Mathematical modelling of forest fires and new methods of fighting them”, Albini, F. (Ed.), Tomsk University, Tomsk.

Morvan, D., Dupuy, J.L., 2001 “Modeling of fire spread though a forest fuel bed using a multiphase formulation”, Combustion and Flame, Vol. 127, pp.1981-1994.

Catchpole W.R., Catchpole E.A., Butler B.W., Rothermel R.C., Morris G.A., Latham D.J., 1998, “Rate of spread of free-burning fires in woody fuels in a wind tunnel”, Combustion Science and Technology, Vol. 131, pp.1-37.

Cheney N.P., Gould J.S., Catchpole W.R., 1998. Prediction of fire spread in grasslands. International Journal of Wildland Fire, Vol. 8(1), pp.1-13.

Alexander M.E., Fogarty L.G., 2002, “A pocket card for predicting fire behaviour in grasslands under severe burning conditions”, Fire Technology Transfer Note, Vol.25.

Linn, R.R., Cunningham, Ph., 2005, “Numerical simulation of grass fires using a coupled atmosphere-fire model: basic fire behavior and dependence on wind speed”, Journal of Geophysical Research, Vol.110, P.1029.

Morvan, D., Dupuy, J.L., 2004 “Modelling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation”, Combustion and Flame, 138, pp.199-210.

Stocks, B.J., Alexander, M.E., Lanoville, R.A., 2004, “Overview of the International Crown Fire Modelling Experiment (ICFME)”, Canadian Journal of Forest Research, Vol.34, pp.1543-1547.

Dupuy, J.L., Morvan, D., 2005, “Numerical study of a crown fire spreading toward a fuel break using a multiphase physical model”, International Journal of Wildland Fire, Vol. 14, pp. 141-151.

Hanson, H.P., Bradley, M.M., Bossert, J.E., Linn, R.R., Younker, L.W., 2000, “The potential and promise of physics-based wildfire simulation” Environment Science Policy, Vol.3, 161-172.

Patton E.G., Sullivan P.P., Davis K.J., 2003. “The influence of a forest canopy on top-down and bottom-up diffusion in the planetary boundary layer” Quarterly .Journal of the Royal Meteorological Society, Vol.129, pp. 1415-1434.

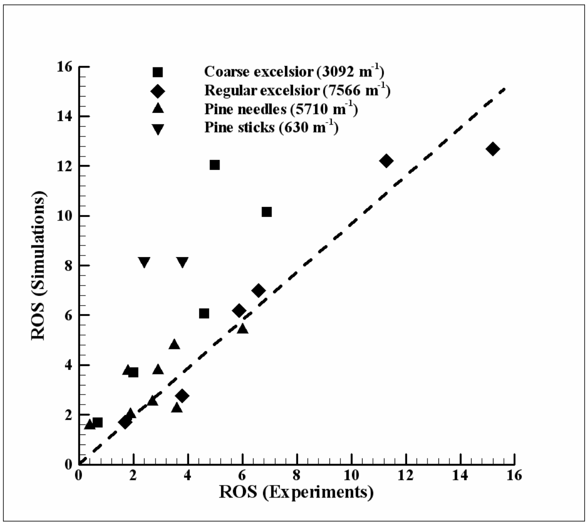

Figure 1: Comparison of the rates of spread (ROS) evaluated numerically and observed experimentally in a fire wind tunnel (Catchpole *et al*, 1998).

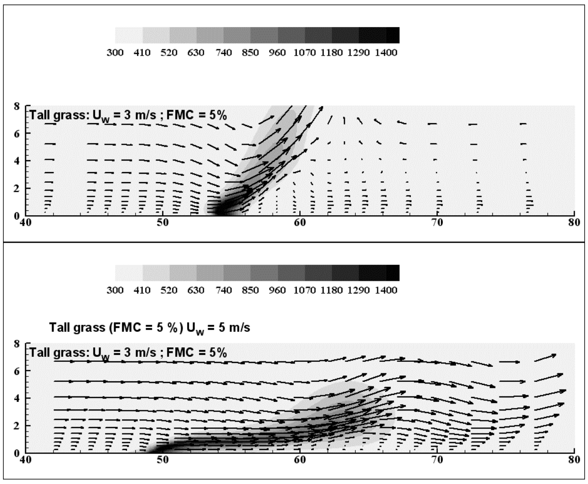

Figure 2 : Temperature and velocity fields (snapshot) calculated during the propagation of a surface fire through a grassland: wind speed velocity $U_W = 3$ m/s (on top), 5 m/s (on bottom), fuel moisture content FMC=5%.

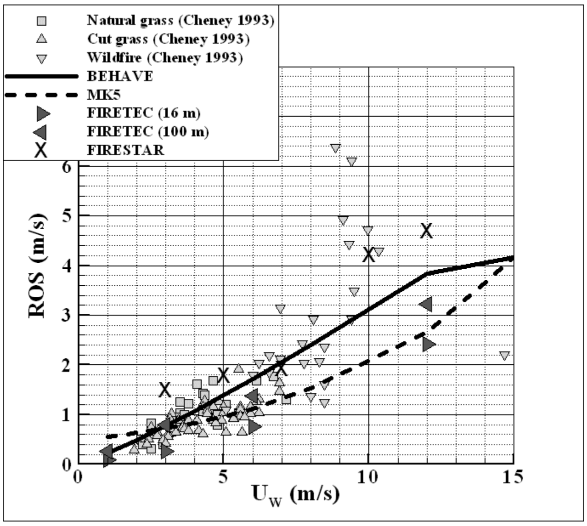

Figure 3: Rate of spread (ROS) as a function of the 10m open wind speed (U_W): Experimental results obtained for natural and cut grassland fires (Cheney & al 1998), predictions obtained using operational tools (*Mk5, BEHAVE*) and numerical results *FIRETEC-3D* and *FIRESTAR* (present model).

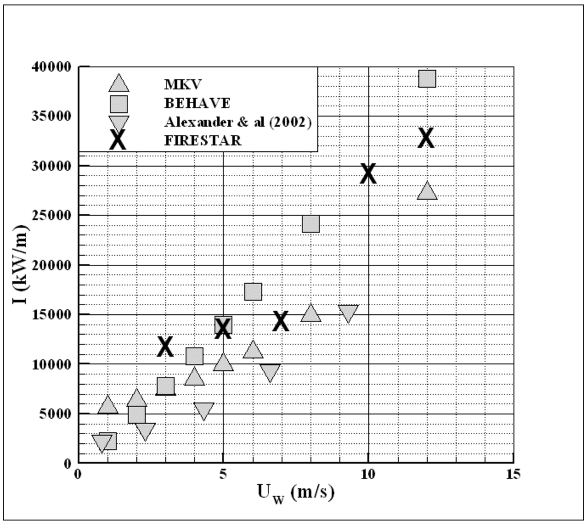

Figure 4: Fire line intensity as a function of the 10m open wind speed (U_W): experimental observation (Alexander 2002) and predictions obtained using operational tools (*Mk5, BEHAVE*), *FIRESTAR* (present model).

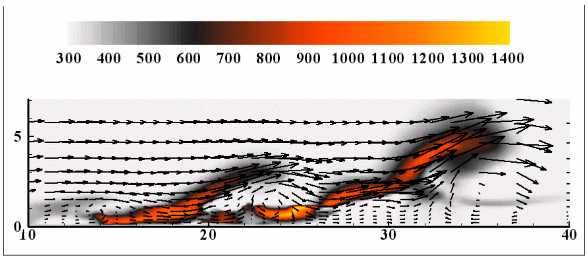

Figure 5: Propagation of a surface fire though a Mediterranean maquis (temperature and velocity fields).

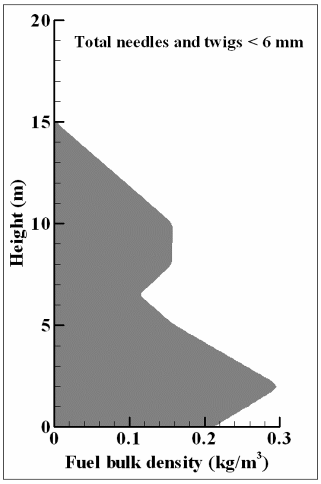

Figure 6: Typical vertical distribution of solid fuel density in a boreal forest.

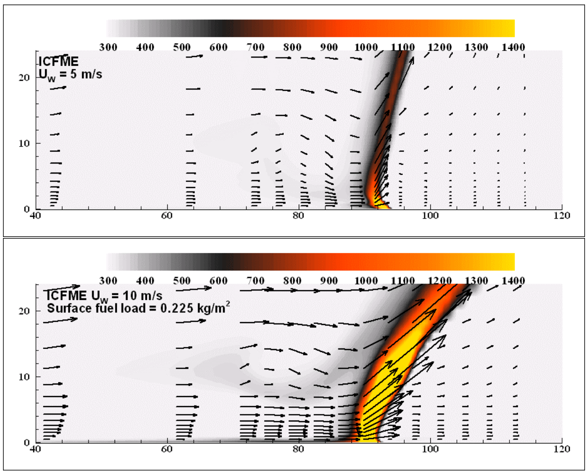

Figure 7 : Temperature and velocity fields (snapshot) calculated during the propagation of a crown fire through a boreal forest: for two values of the wind speed $U_W = 5$ (top) and 10 m/s (bottom).

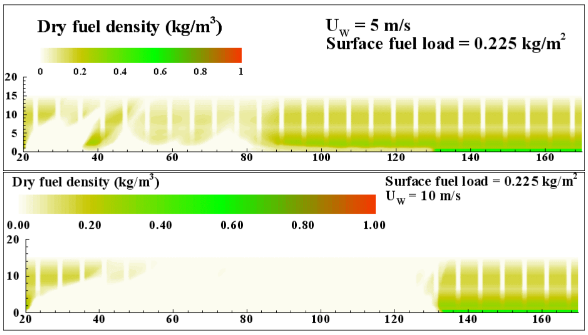

Figure 8: Solid fuel density field (snapshot) calculated during the propagation of a crown fire through a boreal forest: for two values of the wind speed $U_W = 5$ (top) and 10 m/s (bottom).

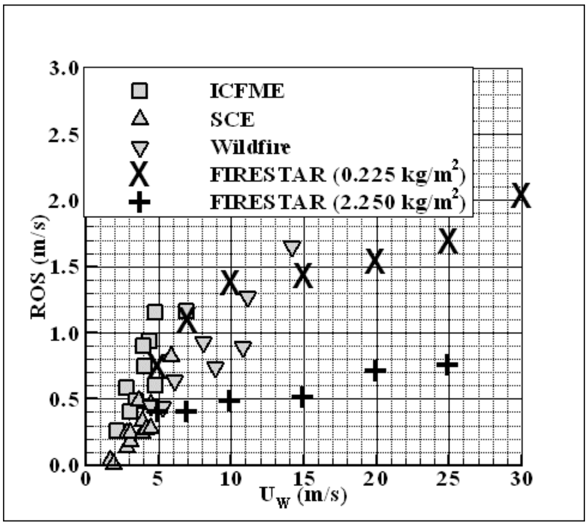

Figure 9 : Rate of spread (ROS) as a function of the 10m open wind speed (U_W): Experimental results obtained during the ICFME campaign (Stocks *et al*, 2004) and numerical results obtained using *FIRESTAR* (present model) for two values of the surface fuel load.