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Fifty years of progress in wildland fire modelling: from empirical to fully physical CFD models

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Abstract. The aim of this short review is to present the progress made in wildland fire modelling during the last 50 years and the intellectual track followed by wildland fires models, from fully empirical models in the 60s, to semi-empirical ones in the 70s, to fully physical models at the end of the 90s. During the last period, the large diffusion of HPC methods substantially contributed to the development of multiphase formulations applied to wildland fire modelling. Many studies have particularly focused on the effects of various parameters (vegetation, topography, atmosphere) affecting the behaviour of a fire front propagating through a forest fuel layer.

Keywords. Wildland fire modelling, Multiphase physical model, Multiphase reactive flow, Turbulent combustion, Wildfire modelling, Radiation heat transfer, Sparce porous media.

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1. Introduction

For various reasons (impacts of global warming, changes in land use, impact of human activities, expansion of wildland–urban interfaces (WUI), etc.) wildfires have become an increasingly dire problem in different parts of the world (in Europe, United States, Canada, Australia, Russia, Indonesia, Brazil, etc.) justifying the growing interest of the scientific community in tackling this "natural" hazard. Experimental fires are relatively difficult to conduct: in the field, they are limited for safety reasons, whereas in the laboratory, small-scale phenomena do not fully reproduce the effects observed at the large scale. For these reasons, the fire safety science

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community has tried for a long time to propose modelling approaches, by adopting a progressive level of complexity, in order to predict the behaviour of wildfires [1–3].

Simulating the behaviour of wildland fires is certainly one of the most challenging problems in thermal and mechanical engineering for several aspects: it is a multi-scale problem (in time and space) that couples several non-linear physical mechanisms (turbulence, combustion, radiation, pyrolysis, etc.). The multi-scale character can be illustrated by the range of length scales acting at different levels on the fire front behaviour: from the turbulent flame thickness (<1 mm) resulting from the combustion process in the gaseous phase to the characteristic length scale associated with the transport of smoke by the convective plume (>100 km). The non-linear character associated with the different physical mechanisms governing the behaviour of a wildland fire contributes also to the high level of complexity of this problem, such as: the degradation process of the vegetation (by drying, pyrolysis, and oxidation), the modes of heat transfer (by radiation and convection) between the flame, the hot gases, and the vegetation, the interaction between the atmospheric boundary layer (the wind) and the vegetation, the turbulent combustion in the flame, and others [4]. Somehow, such a problem could be considered too much complicated to be tackled using simulation tools. For all these reasons, wildfire modelling has been limited for a long time to empirical models, obtained from more or less numerous experimental fires performed through homogeneous fuel beds in laboratory, in homogeneous grasslands in the field [5], and in more heterogeneous combustible layers such as shrubland and forests [6]. However, even if this approach, often called "burn-to-learn", has known some success in homogeneous vegetation cover (such as grassland) which is frequently encountered worldwide (in Africa, Australia, the United States, etc.), it has been difficult to generalize for more heterogeneous media such as heathlands and forests. The other reason justifying the progress towards a more physical approach was that empirical relationships do not impart a real understanding of the physical parameters (vegetation, topography, wind, etc.) governing the behaviour of wildfires, their associated mechanisms, or their relative importance [4, 7, 8]. In addition to improving the fundamental knowledge of wildfire behaviour, there are also more practical applications associated with fire safety engineering, that can reduce wildfire hazard and the impacts upon the ecosystems and communities. CFD-based fire modelling tools can contribute, for example, to improve the management of fire risk in WUI, in recreation areas such as national and regional parks, with a particular interest to improve the decision support systems associated with the fuel reduction operations [9].

This is this story that we propose to summarize in this short review.

2. From semi-empirical to fully physical wildfire modelling

Even if the literature reports early publications in the 40s and the 60s [10, 11] on physical aspects associated with wildfire behaviour, we have chosen to begin this story from the papers proposed by Frandsen, Anderson and Rothermel [12–14]. The main interest of these works, in comparison to purely empirical works, was to propose an evaluation of the rate-of-spread (ROS) of a surface fire through a homogeneous solid-fuel layer, based on physical considerations. This class of model was based on an energy balance written in an inertial reference frame attached to the fire front (assuming steady state conditions) between the enthalpy required to sustain fire propagation and the energy received by the unburned vegetation located ahead of the fire front. The key point to solve this balance equation was to propose an evaluation of the ratio between the energy received by the vegetation and the energy released by the fire itself. In the model proposed by Anderson and Rothermel [12, 14], this ratio was assumed to be a function of the surface area to volume ratio (inversely proportional to the thickness) of the solid particles composing the fuel layer. This relationship was evaluated from a set of experimental fires performed on a fire table and in a fire wind tunnel. The effects of slope and wind on the ROS were accounted for through a correction factor that multiplies the ROS evaluated for a fire propagating on a flat terrain without wind. Without any doubt, the main advantage of this model is its simplicity, it is for this reason that it was implemented in the most used operational tool in the world: FARSITE [15]. In FARSITE, the terrain topography was coupled to a vegetation layer library of various kinds of ecosystems (grass, litter, shrub, etc.). With the wide use of FIRESITE around the world, this vegetation layer library is continuously enriched. Compared to a purely empirical approach, this simplified physical model represented the promise of developing an engineering tool having the capacity to be adapted to a large variety of ecosystems and external conditions (slope, wind, fuel moisture content, etc.), without the need of powerful computing means. For these reasons it has known a great success worldwide. However, we must underline that one of its major limitations is that the experiments used to calibrate the constants of the model were performed at the small scale, in solid fuel litters with pine needles or excelsior. For various reasons (compactness of the fuel layer, low level of turbulence, low fuel moisture content, dimensions of the vegetation layer, etc.), the conditions reproduced in such experiments covered a range of situations too small to apply the model to all configurations observed at large scale on the field. In conclusion, this semi-empirical model is actually considered to be limited by scale effects and must be improved by the addition of new data sets from experimental fires carried out in the field and also in the laboratory using artificial reconstituted fuel less compact than forest litter (work in progress) [16]. As a consequence of this initial defect, the value of the ROS predicted by the model in some configurations (mainly at large scale) were larger than the local wind speed, which is quite difficult to understand, especially if the wind intensity is significant. However, comparisons between direct observations of the dynamics of the 1996 Malibu fire (October 22, 1996) and numerical simulations have shown that the introduction of the modifications induced by the topography on the atmospheric flow in FARSITE (i.e. the Rothermel's model) significantly improved the predictions [17]. This result, among others, motivated different research teams to couple a simplified fire spread model (such as Rothermel's) with a mesoscale atmospheric model [18–20]. For operational applications, requiring the simulation of wildfire propagation at a regional scale, this coupled approach is considered to be very promising and is still in progress with the arrival of new (more physical) fire propagation models such as Balbi's model [21, 22].

The two main differences between semi-empirical fire models and coupled mesoscale atmospheric fire models is the treatment of the wind flow in interaction with the fire front and the vegetation description. As illustrated in Figure 1, in semi-empirical models, the wind flow is assumed to be uniform everywhere and equal the wind intensity given by the general meteorological conditions. In this case the variability of the wind flow in the atmospheric boundary layer is not taken into account and the problem is reduced to the propagation of a fire line along a curved surface (Figure 1 on top). For coupled mesoscale atmospheric fire models, the atmospheric boundary layer is effectively calculated, the influence of the topography is taken into account, as well as the effect of the fire itself. The flame is not explicitly simulated but its presence is accounted for by injecting a heat flux at the location where the fire front is supposed to be (Figure 1 in the middle). Both for semi-empirical models and coupled mesoscale atmospheric fire models, the vegetation layer on the ground is not explicitly described, it is reduced to a curved surface, with the introduction of a surface shear stress to reproduce the ground roughness and a heat flux to reproduce the heat released from the fire. In some cases a relatively rough representation of the vegetation can be introduced and coupled with an atmospheric fire model [23]. The presence of the flame and of the vegetation (Figure 1 on bottom) is more explicitly represented only with the last generation of wildfire models detailed in the next section.

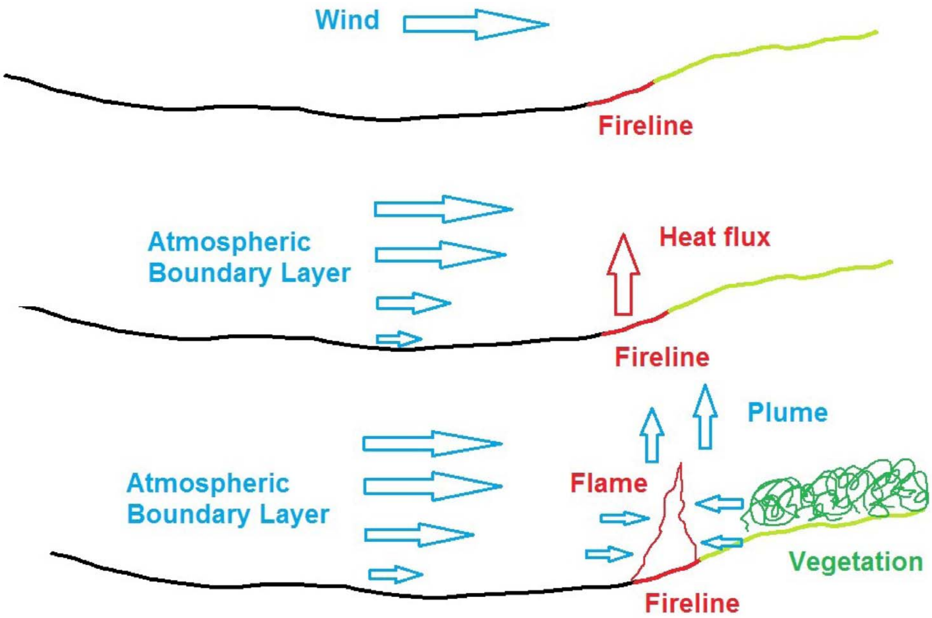

Figure 1. Hierarchy of wildfire models from semi-empirical models (top), to coupled mesoscale atmospheric fire model (middle), to fully physical models (bottom).

3. Toward a detailed physics-based wildland fire model

In addition to operational needs, the necessity for more fundamental studies has also been identified in order to improve knowledge of wildfire behaviour. Following the "burn-to-learn" concept, this objective can be achieved through campaigns of experimental fires [24], but also using mathematical models and numerical simulations. Most of these works are based on a multiphase formulation, assimilating the vegetation layer to a sparse porous media and applying an additional homogenization step to establish the set of equations governing the behaviour of the coupled system formed by the vegetation and the surrounding ambient air [25–28]. A similar approach had previously been introduced to simulate the interaction between the atmospheric boundary layer and a forest canopy [29, 30]. For wildland fires, the monograph published by Grishin in English in 1997 [31] (many Russian papers had been published earlier) can certainly be considered one of the major contributions to initiate this approach. This kind of model consists of coupling two sets of differential equations: one for the gaseous phase and the other for the vegetation layer, reproducing the time evolution of variables governing the behaviour of a fire front propagating through a vegetation stratum. The vegetation is assimilated to a set of families of solid fuel particles, representing the various vegetal species and the various elements (foliage, twigs, etc.) composing the fuel. Each solid fuel family is locally represented as a mixture of dry matter, water, charcoal, and ashes; the mass fraction of these four elements varies according to the degree of vegetal decomposition. Under the intense heat flux coming from the flame front, these solid fuel particles will be degraded into gaseous products (water vapour, carbon monoxide, carbon dioxide, methane, etc.) and solid products (charcoal) that can eventually transform by homogeneous and heterogeneous combustion. Concerning the resolution of the boundary layer flow, the presence of the vegetation results in the introduction of volume drag forces proportional to the leaf area density (LAD) representing the density of contact surface between the solid phase and the surrounding gas [32]. As suggested in Figure 1, in addition to the calculation of the turbulent atmospheric boundary layer flow, this kind of wildfire model also includes the explicit resolution of the turbulent flame forming the fire front and consequently the heat flux by convection and radiation between the flame and the unburnt solid fuel. Due to this high level of complexity, such an approach is limited to simulating fire behaviour at a local scale (few hectometres) and its application must be limited to fundamental studies in order to improve knowledge of wildfire dynamics and to fire safety engineering studies around some potential targets such as buildings located in WUI [27,28,33–35]. The degree of complexity of such models also increases the level of uncertainty of various parameters affecting the fire behaviour; therefore, as in other CFD applications, it is always necessary to enforce the confidence that we attribute to results obtained from these fully physical models by comparing them to experimental data [35].

Combined with theoretical analysis [36], detailed physics-based wildland fire models have allowed to highlight the role played by two forces governing fire behaviour: buoyancy and wind inertia. Buoyancy results from temperature difference between the thermal plume and the ambient air, it contributes to maintaining the flame and the plume as vertically as possible. One of the main advantages of fully physical models, is it capability to access directly, independently and without arbitrary assumptions, to various parameters characterizing the fire behaviour, such as the rate of spread and the fire intensity. As a numerical experiment, this approach allows access to a wide range of information, in order to test some assumptions and by this to understand more deeply physical phenomena governing fire behaviour. Wind inertia is due to the action of the wind flow that pushes the flame and the plume horizontally. As a consequence of that, the main parameter characterizing fire behaviour depends on the ratio between these two forces; similar to an inverse Froude number, it is referred to in the literature as Byram's convective number (N_C) and given by (1) [4,36,37]:

$$N_C = \frac{2gI}{\rho C_P T_0 (U_W - \mathrm{ROS})^3}, \tag{1}$$

where g is the gravitational acceleration, I is the fireline intensity (i.e., the thermal power per unit length released by the fire, expressed in W/m), ρ, C_P, and T_0 are respectively the density, the specific heat, and the ambient air temperature, U_W and ROS are the wind velocity and the fire rate of spread. As an example of the dependence of wildfire behaviour on Byram's convective number, both experimental observations and numerical results have shown (at least for a surface fire on a flat terrain) that the ratio U_W/ROS decreases as the value of $1/N_C$ increases, to reach a value that seems only to depend on fuel moisture content (FMC) [36,38]. In this case, two regimes of fire propagation have been identified [38]: plume dominated fire ($N_C > 10$) and wind driven fire ($N_C < 2$) [36], respectively privileging heat transfer between the flame and the vegetation by radiation and convection. On the other hand, direct observations of a fire front clearly showed that it is far from being assimilated as a homogeneous radiant panel, on the contrary, it is structured in peaks and troughs as shown by Figure 2 illustrating a 3D numerical simulation of a surface fire propagating through a homogeneous vegetation cover (a grassland in this particular case). For this calculation, periodic boundary conditions had been imposed on the two lateral sides, in order to reproduce a quasi-infinite fire front [34, 39]. Numerical simulations have also been performed for heterogeneous vegetation layers, such as pine forest [31], Mediterranean shrubs [33], or even a single tree [35]. In such configurations, because the size of the fuel elements and their FMC can substantially vary within the fuel complex, the description of such vegetation layer cannot be reduced to a single type of solid fuel particles, with significant impacts on the fire dynamics [32, 33, 35]. As an illustration of this idea, Figure 3 shows two snapshots of the gas temperature field obtained numerically during the burning of a single tree (Douglas fir) using four types of solid fuel particles, representing the needles and three different-diameter twigs (1.5, 4.5, and 8 mm). The mass loss rate (MLR) obtained for this kind of configuration, using

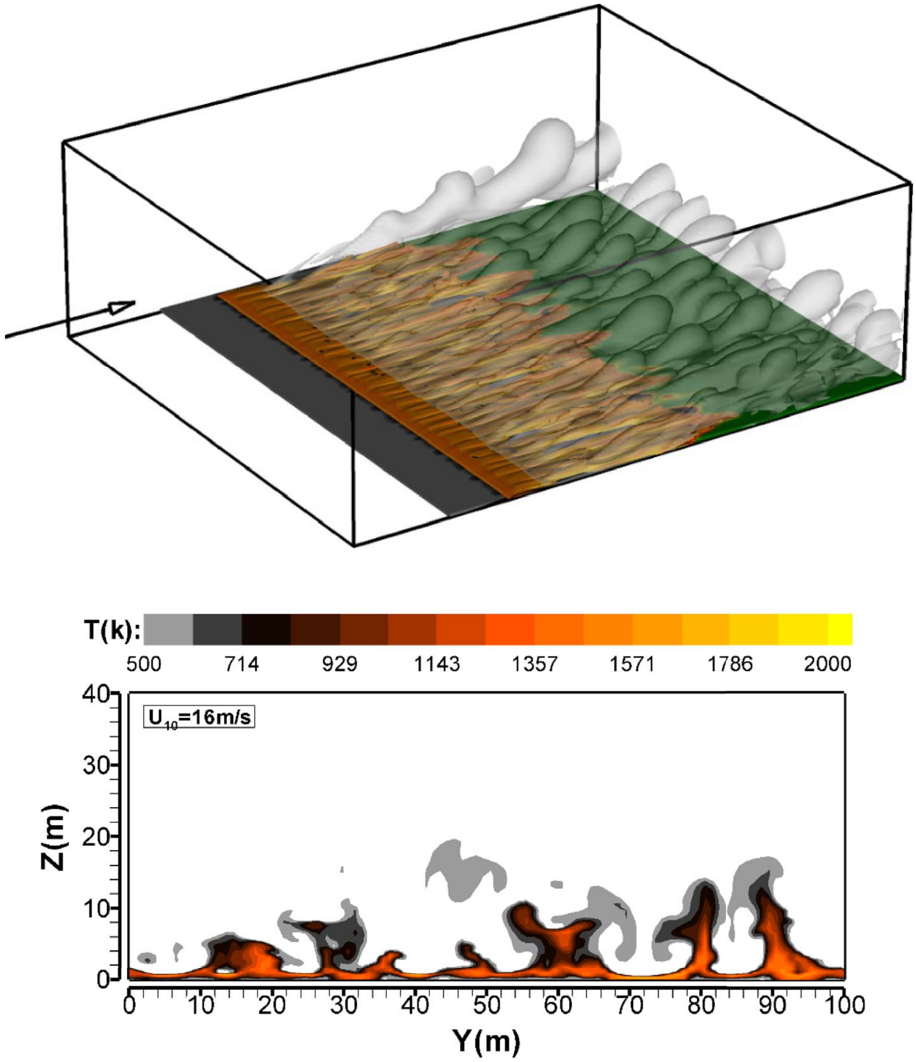

Figure 2. Numerical simulation (3D view and 2D vertical cut along the fire line) of a quasi-infinite long fire front propagating through a grassland (gas temperature).

two fuel description models (with one and four fuel types) is represented in Figure 4. These results illustrate clearly the case for increasing the level of complexity of the representation of the vegetation, in particular they highlight the role played by the distribution of solid fuel size upon the fire dynamics.

4. Conclusion

This short review was dedicated to summarize the progress made since the 70s in forest fire modelling, beginning with empirical and semi-empirical models and ending with fully physical models operating nowadays. Given the multi-scale and strongly non-linear character of this problem, we can conclude that a unique approach cannot answer all the needs of the wildfire community, from basic physical knowledge of wildfire behaviour to operational forecasting of a

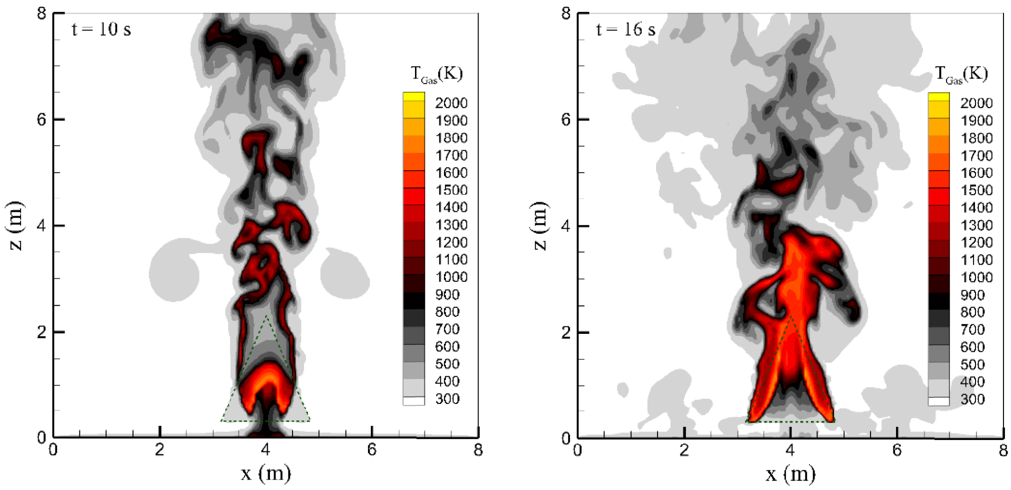

Figure 3. Numerical simulation (gas temperature) of the burning of a single tree represented using four solid fuel types at two different times.

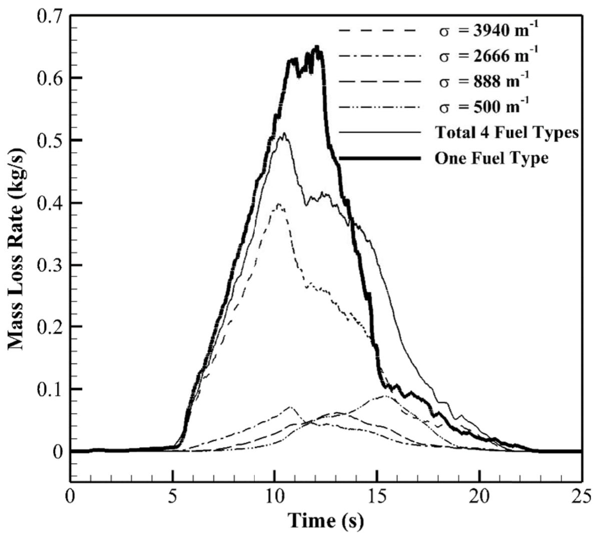

Figure 4. Time evolution of the mass loss rate (MLR) calculated for a burning tree simulation using two descriptions of the fuel with one fuel type (needles) and four fuel types (needles and twigs of various diameters).

fire front propagation at a regional scale. To improve the knowledge about wildfire behaviour and fire propagation mechanisms, and to propose solutions for fire safety engineering in WUI, detailed physical wildfire models can be considered as a promising approach. Whereas, if the objective is the forecast of a fire front propagation, of a fire plume and other impacts of wildfires at a regional scale, coupled atmospheric models with simplified fire models (that can be improved as wildfire knowledge progresses) will remain for a long time the only effective operational solution.

Conflicts of interest

Authors have no conflict of interest to declare.

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