Preliminary Study of Wildland Fires

P. Ciambelli, L. Malangone, P. Russo, S. Vaccaro

Department of Chemical and Food Engineering, University of Salerno Via ponte don Melillo 84084 – Fisciano (SA) ITALY

1. Introduction

Over the last decades, wildfires phenomenon has assumed alarming proportions. Woodlands in rural areas or at the interface with urban areas still continue to burn with significant environmental, social and economic impacts, in particular in case of increased frequencies of fires. As a response, a number of technologies have been developed for the management of environmental emergencies. Since fire behavior and propagation is one of the most critical aspect of the decisional structure during emergencies, for a decision support system the development and the validation of a model for short term prevision of fires propagation is of primary importance.

In wildland fires, flaming combustion of lignocellulosic fuels occurs when the gases released from the thermal degradation ignite in the surrounding air. Then the heat of combustion causes the thermal degradation of adjacent virgin fuel. A successful fire spread (speed of the fire) occurs when sufficient energy is transferred from the flame front to the unburnt solid fuel, resulting in an increase in the fuel temperature to its ignition point. The solid phase temperature is the result of interacting radiative, conductive, and convective heat transfer. In addition, water vaporization, pyrolysis, and fuel combustion also influence the solid phase temperature.

Fire spread is not only the propagation of fire following the terrain slope, but also the propagation of fire from surface fuels (litter, grass, shrubs) to crown fuels (foliage of tree crowns). Knowledge of these effects and their quantification is crucial for the phenomenon prediction.

Since the difficulty in performing real scale tests, a range of wildfire behaviour models exist, which vary in both complexity and computational cost: empirical models (based primary on statistics collected by observation of experimental or historical fires) [1], semi empirical models (based on physical laws, but enhanced with some empirical factors) that are widely used as operational tools [1], and physical models which attempt to solve the equations governing fluid dynamics, combustion, and heat transfer, accounting for the fire/atmosphere and the fire/fuel interactions [2]. The problem involves strong interaction between non-linear phenomena such as the turbulence in the lower part of the atmospheric boundary layer, chemical reactions, radiation heat transfer in the flaming zone, and the degradation of heterogeneous media representing the vegetation and its interaction with the ambient gas mixture (air, pyrolysis and combustion products).

In this context the present work aimed at studying fires propagation by means of a CFD code properly modified to be able to simulate fire spreading among different kind of fuels (trees, shrubs and ground litter). Mathematical tools applied to this kind of environment can be used to understand how fires spread in a forest, to help train fire fighters and to quantify the benefits of mitigation actions**.** Due to the complex phenomena involved in simulation, detailed data on the topography, local meteorology, elevations, three-dimensional distributions of natural fuels, and their properties are needed [3].

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2. CFD modeling of Wildland Fires

In open field fire modeling, the difficulties associated with the analyses of the related phenomena arise from the wide range of length and time scales that exist within the established flow regime (turbulent reacting flow). Firstly, the combustion zone above the fuel source is a region where the local mixing of gasified fuel and air reacts to produce combustion products associated with the release of chemical energy and emission of radiant energy. These processes, considered to be microscopic in nature, can occur on length scales ranging from a fraction of a millimeter to a few centimeters. Secondly, the combustion zone represents a source of buoyancy, which induces large-scale mixing of the air and combustion products, forming a plume, which can prevail as an organized structure over length scales covering meters or tens of kilometers, depending on the fire scenario of interest.

According to this complexities and considering the availability of limited computing power and resources, a lot of efforts have been invested in the formulation of appropriate models describing combustion, radiation, soot production and pyrolysis, in order to increase the sophistication of fire modeling without increasing the demand of computational resources. In computational flow dynamics (CFD), the most accurate approach to turbulence simulation would be to solve directly the governing transport equations, without undertaking any averaging or approximation other than the consideration of appropriate numerical discretisations performed on them. Commonly known as the direct numerical simulation (DNS), this approach requires all significant turbulent structures to be adequately captured or fully resolved. This means that the domain of which the computation is to be carried out requires resolution of the largest as well as the smallest turbulent eddies.

Alternatively, the approach where the structure of turbulent flow is viewed as distinct transport of large- and small-scale motions results more convenient. On this basis, the large scale motion that governs the mixing of gases is directly simulated while the small scale motion is sligtly accounted for or ignored. The possibility to operate such an approximation, in what is recognized as large eddy simulation (LES), should be justifies by experiments, but it gives the opportunity to significantly reduce computational costs respect to DNS. Numerical results obtained from a DNS or LES simulation, generally contain very detailed information about the flow: they have the capacity of attaining increasing realism and because of the wealth of information, DNS and LES can provide a qualitative understanding of the flow physics and construct a quantitative model.

3. WFDS simulations

The Wildland Fire Dynamic Simulator (WFDS), developed by the US National Institute of Safety Technology [4], is an extension of the model developed to predict the spread of fire within structures, Fire Dynamic Simulator (FDS) [5]. This model is fully 3D, is based upon a unique formulation of the equations of motion for buoyant flow [6] and is intended for use in predicting the behavior of fires burning through periurban/wildlands. The main objective of this model is to predict the progress of fire through predominantly wildland fuel augmented by the presence of combustible structures. WFDS utilizes a varying computational grid to resolve volumes as low as 1.6m(x)×1.6m(y)×1.4m(z) within a simulation domain in the order of 1.5 km^2 in area and 200 m high. Outside regions of interest, the grid resolution is decreased to improve computation efficiency.

The model includes features such as momentum drag caused by the presence of the grass fuel which changes over time as the fuel is consumed. Mechanical turbulence, through the dynamic viscosity of the flow through the fuel, is modeled as a subgrid parameter via a variant of the LES method. The WFDS assumes a two-stage endothermic thermal decomposition (water evaporation and then solid fuel 'pyrolysis'). It uses the temperature dependent mass loss rate expression of Morvan and Dupuy [7] to model the solid fuel degradation and assumes that pyrolysis occurs at 127◦C. Solid fuel is represented as a series of layers which are consumed from the top down until the solid mass reaches a predetermined char fraction at which point the fuel is considered consumed.

There are two types of combustion models used in WFDS. The default model makes use of the mixture fraction, a quantity representing the fuel and the products of combustion. For the second model, individual gas species react according to specified Arrhenius reaction parameters. Char oxidation is not accounted for.

This latter model is often used in a DNS where the diffusion of fuel and oxygen can be modeled directly. However, most often for large eddy simulations, where the grid is not fine enough to resolve the diffusion of fuel and oxygen, the mixture fraction-based combustion model is assumed. Using the mixture fraction model, each reaction is assumed to be of the form:

$$C_x H_y O_z N_v Other_w + \upsilon_{O_2} O_2 \rightarrow \upsilon_{CO_2} CO_2 + \upsilon_{H_2O} H_2O + \upsilon_{CO} CO + \upsilon_{Soot} Soot + \upsilon_{N_2} N_2 + \\ + \upsilon_{H_2} H_2 + \upsilon_{Other} Other \quad (1)$$

Where, to define the chemical formula of the gaseous fuel, the yields of product and/or the amount of the species C, H and O forming the main reactant needs to be specified along with the heat of combustion. Unless performing a DNS, the reaction rate of fuel and oxygen is not based on a diffusive transport; instead, semi-empirical rules are invoked by the software to determine the rate of mixing of fuel and oxygen within a given mesh cell at a given time step. This approach, even not completely rigorous, has been proved to be valid in successfully modeling the burning of a single tree [8]

The energy release, associated with chemical reactions, is not explicitly presented but is accounted for by an enthalpy variable as a function of species. The model assumes that the time scale of the chemical reactions is much shorter than that of mixing. Thermal radiation transport assumes a gray gas absorber-emitter using the P1 radiation model for which the absorption coefficient, for a given mixture of species, is a function of the mixture fraction and temperature. A soot production model is not used; instead it is an assumed fraction of the mass of fuel gas consumed.

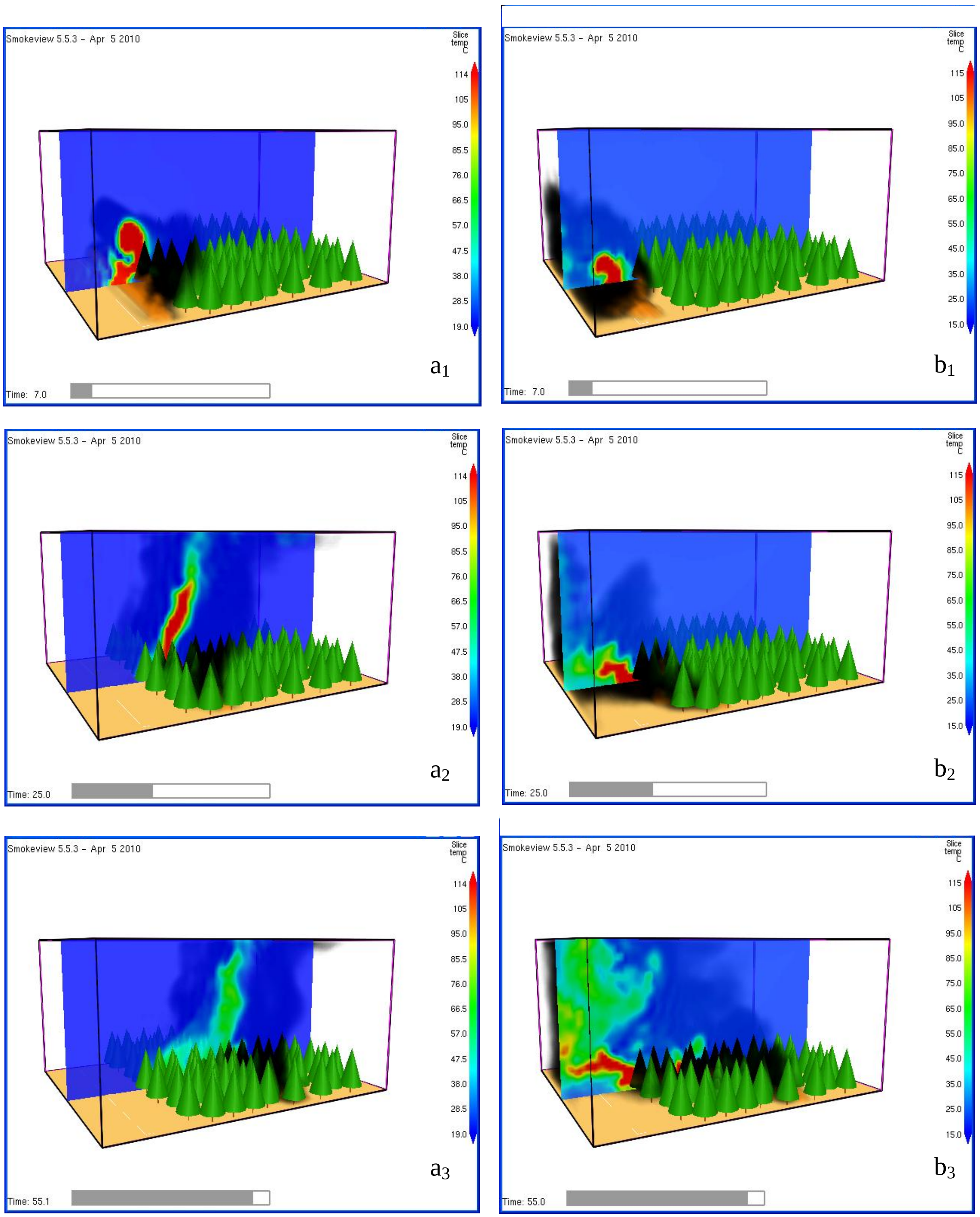

Figure 1: Random distribution of 90 identical 6 m tall, 3 m wide cone shaped trees arranged in a 30 m wide and 25 m long area. A 0.5 m tall grass is underneath the trees. The grass is ignited along a line on the left side of the pictures. The wind speed is 2 m/s blowing parallel to the tree-plane toward the trees in pictures 1a and in the opposite direction in pictures 1b. From top to bottom subscripts 1, 2 and 3 refer to snapshots at 7, 25 and 55 seconds from the ignition, respectively.

Simulation depicted in Figure 1 models the effect of wind direction on the propagation of fire across a random distribution of trees and was performed using the software WFDS. Since WFDS works considering the LES approach, particular attention needs to be paid when building the mesh for domain discretization. Large eddy simulation technique is based on the assumption that the numerical mesh should be fine enough to allow the formation of eddies that are responsible for the mixing. In general, eddy formation is limited by the largest dimension of the mesh cell, which was set to 0.5 meters.
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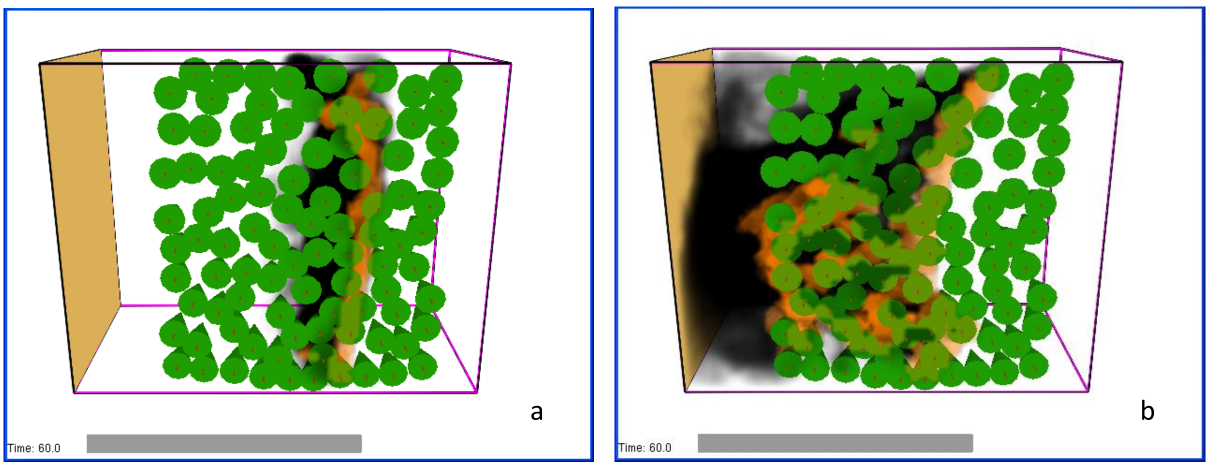

Figure 2: Fire propagation from an up-side wiev of the tree distribution depicted in figure 1 at 60 seconds from ignition. The wind speed is 2 m/s moving parallel to the tree-plane from the brown surface toward the trees in Figure 5a and in the opposite direction in Figure 5b.

From Figure 1 the effect of wind over fire propagation may be easily evinced, showing how flame and smoke spreading becomes strongly affected by wind direction. In both figures, the temperature profile along a symmetric plane perpendicular to the trees surface is considered. Due to the large-scale mixing of the air and combustion products, the temperature gradient shown on the blue plane is depicted as a plume, which assumes different configuration according to wind conditions.
A deeper analysis on the effect of wind in the analyzed domain can be deduced from figure 2, where the spreading of the fire, developed in both wind situations, was taken considering an inverted point of view. In figure 2a, fire distribution tends to assume a circular profile, typical pattern of flames spreading across grass [5]: fire movement is almost not affected by the presence of the trees due to the limited development of crown fire. Instead, Figure 2b shows clearly a 'slowing' effect of wind over fire propagation; in this case, however, a more chaotic fire development with respect to that shown in figure 2a was reached.

4. Conclusions

The prediction of wildland fire behavior using physic-based model is an application that presents many substantial scientific, computational, and forecasting challenges. The current implementation of WFDS is for research applications since it requires significant computational resources, computer time, and can be demanding in terms of input information (wind, fuel, and terrain conditions). From this point of view, empiric or semi-empiric-based model may result to be more convenient as fire dynamic simulator even if, by necessity, they have more approximations to the physical processes and their limitations need to be determined through comparison with field measurements. A number of simpler approaches are being investigated; these include models that account for the entrainment of air by burning buildings and its effect on a spreading grass fire on flat [9] and hilly [10] terrains.
However, physics-based models can provide fire behavior predictions over a realistically broad range of fuel types under a variety of weather and terrain conditions. A range of model approaches, with sufficient experimental and field measurement support, could be used to test and improve risk assessment and mitigation strategies for realistic fuels and environmental conditions. While such a task, especially with large-scale field measurements, would be expensive, the cost of not undertaking such a research program could even be more expensive in the long term.

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