Physical phenomena governing the behaviour of wildfires : numerical simulation of crown fires in boreal forest

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Résumé :

Cette étude est consacrée aux mécanismes physiques contribuant au comportement des feux de forêt. Le problème a été formulé en utilisant une approche multiphasique, comprenant l'ensemble des équations de conservation gouvernant le système couplé formé par la végétation et la couche atmosphérique située au voisinage immédiat du front d'incendie. Quelques exemples de simulations réalisées pour des feux de cimes se propageant en forêt boréale ont pu être comparées avec des données expérimentales collectées au cours de campagnes expérimentales réalisées dans les Territoires du Nord-Ouest au Canada.

Abstract:

This paper deals with a presentation of the physical phenomena contributing to the behaviour of wildfires. The problem was formulated using a multiphase approach, including the set of balance equations governing the coupled system formed by the vegetation and the surrounding atmosphere in the vicinity of the fire front. Some numerical simulations carried out for a crown fire in boreal forest are compared to data collected during an experimental campaign conducted in the North West territories in Canada.

Mots clefs: **Combustion, Modélisation des feux en milieu naturel**

1 Introduction & physical model

Many factors, such as the expansion of the wildland urban interface (WUI) at the periphery of large cities, the deficit of rain falls resulting from the first manifestations of global warming, contribute to aggravate wildfire hazard, especially in Mediterranean regions (around Mediterranean basin, in Iberic peninsula, in South western USA, in Australia) but also in boreal regions (northern USA, Canada, Russia). It is in this context that many studies based on a physical approach, were recently proposed to simulate wildfires, in order to understand the basic mechanisms governing the propagation of the fire front through a vegetation layer [1, 2, 3]. Two basic mechanisms contribute to the heat transfer between the flame and the unburned vegetation: the radiation coming from the soot particles located in the flame and the convection heat transfer between the hot gases coming from the burning zone and the vegetation located ahead of the fire front. The relative importance between these two mechanisms of heat transfer, results from the competition between two forces: the inertia due to the wind flow and the buoyancy resulting from the gradient of density between the hot plume above the fire and the ambient air [4]. Analysing the fire residence time, measured experimentally for various homogeneous fuel beds, demonstrated that only very fine particles (thickness smaller than 6 mm) composing the fuel complex, contributed effectively to the propagation of a fire. Taking into account of all these informations, a multiphase formulation was proposed to simulate the propagation of wildfires at a relatively local scale (<200 m) [1, 5]. Basically, this model consists in solving two problems: a first one to calculate the turbulent reactive flow in the gaseous phase and a second one to calculate the evolution of the state of a set of solid fuel families representing the vegetation. These two problems include some additional terms (drag forces, heat and mass transfers) representing the coupling between the gaseous phase and the vegetation. Assuming that the combustion rate in the fire was mainly limited by the mixing between the combustible gas resulting from the thermal decomposition of the vegetation (by pyrolysis) with the oxygen of the ambient air, the turbulent transport and the combustion in the gas phase were simulated using an eddy viscosity model (k-ε RNG model) and the eddy dissipation concept (EDC) (for details see reference [4]). The radiation heat transfer was also simulated, assuming that the maximum value of the production rate of soot particles in flames, was a fixed ratio of the rate of pyrolysis, moderated by the local mass fraction of oxygen. The radiation transfer equation (RTE) was solved using a Discrete Ordinate Method (DOM), introducing some additional contributions resulting from the turbulence radiation interaction (TRI) (using an optically thin fluctuation approximation) [6].

2 Numerical Results & Discussion

To illustrate the possibility of the model, we present some numerical results obtained during the propagation of a crown fire (affecting all the solid fuel located between the ground and the tree top) in a boreal forest. In this case, the vertical structure of the fuel (see Figure 1) was composed with two layers: a continuous distribution near the ground representing the understorey vegetation (shrubs) and a periodic distribution representing the canopy. In this case, the numerical results showed clearly (see Figure 2), how the atmospheric flow can be significantly affected by the presence of the vegetation (drag effect) and by the flame front (in draft flow). We also studied, how the canopy (twigs, foliage) in a forest, can be affected by a fire initially ignited in the shrubs layer (Figure 3). Analyzing the temperature fields calculated for the gas phase, and for some solid fuel families (see Figure 3), we noticed that the convection heat transfer between the hot gas in the plume and the vegetation was the main physical mechanism governing the propagation of the fire. In the region located ahead of the fire front, at the top of the canopy we noticed a zone where the temperature of the foliage was a little bit larger than the temperature of the gas (ΔT<30 K), indicating that the radiation heat transfer cannot be completely neglected (even if its role remained minor) for this problem. Some general physical parameter, describing the behaviour of the fire (such as the rate of spread and the fire intensity) were also compared to experimental data collected during a campaign carried out in the Northwest Territories in Canada [7].

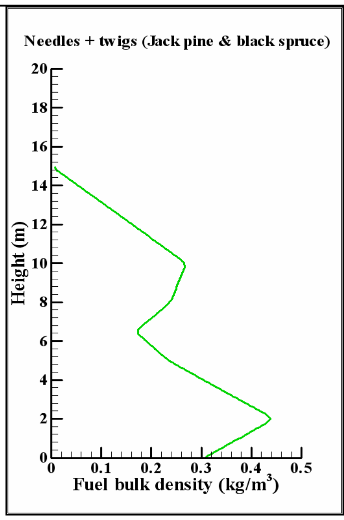
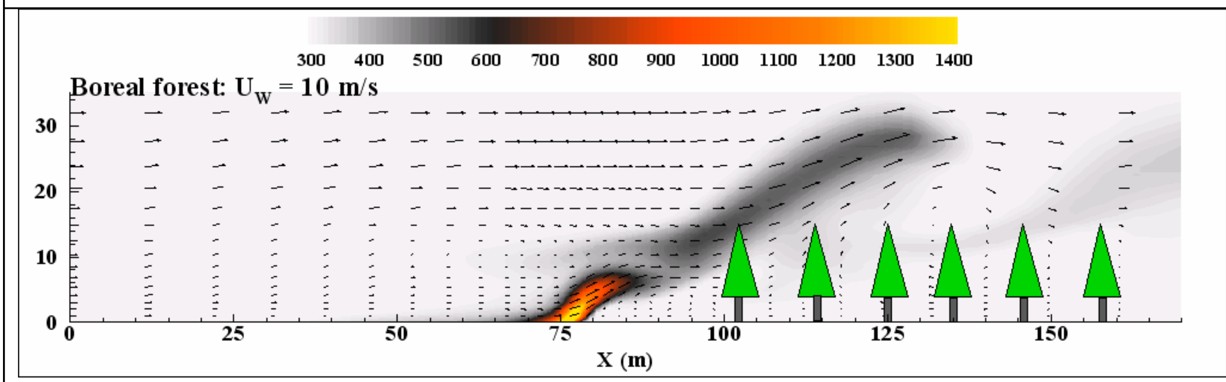


FIG. 1: Structure of the vegetation (left) and vertical distribution of solid fuel density (right) in a boreal forest.



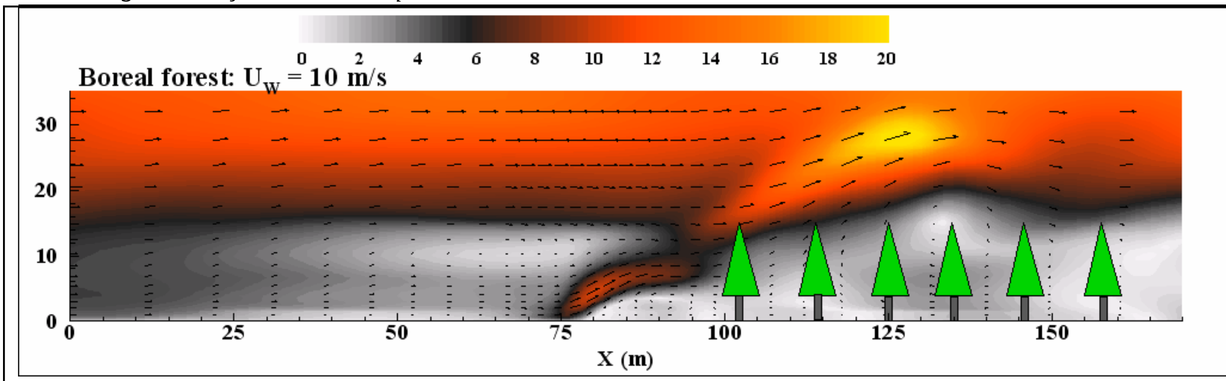
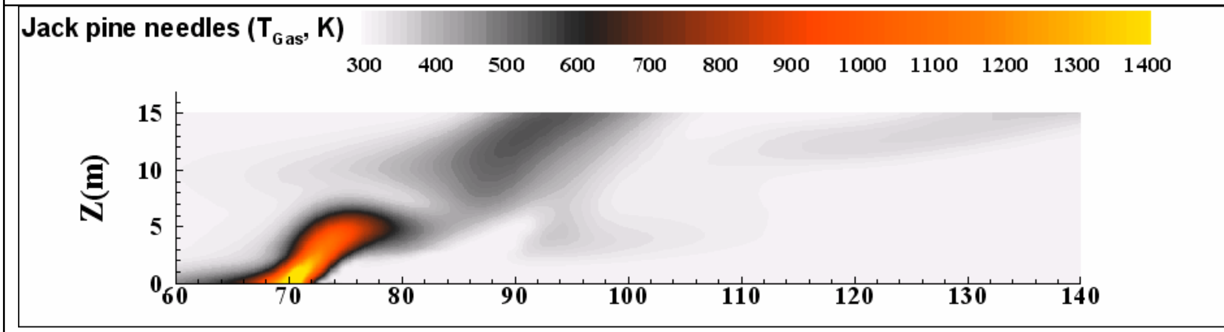
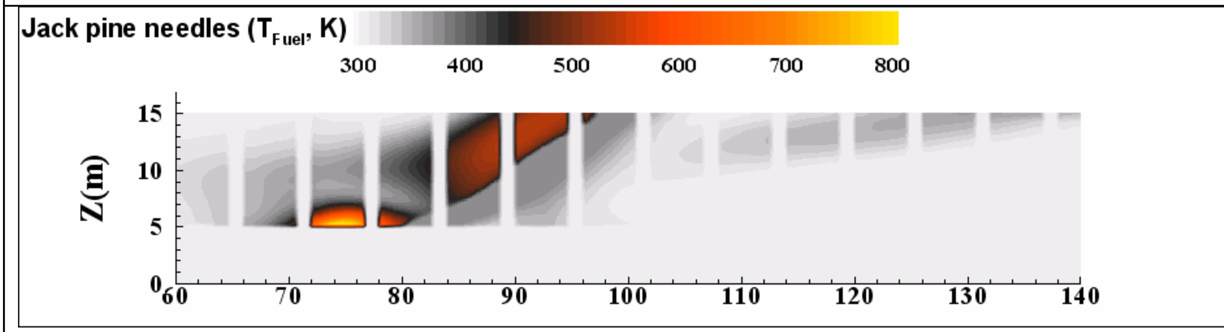


FIG. 2: Velocity vectors, temperature field (gas) (on top) and velocity magnitude (on bottom) calculated during the propagation of a fire through a boreal forest.





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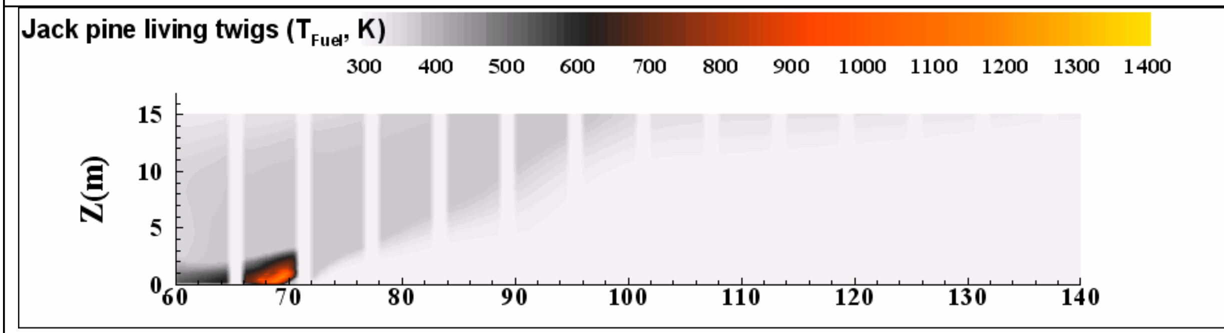

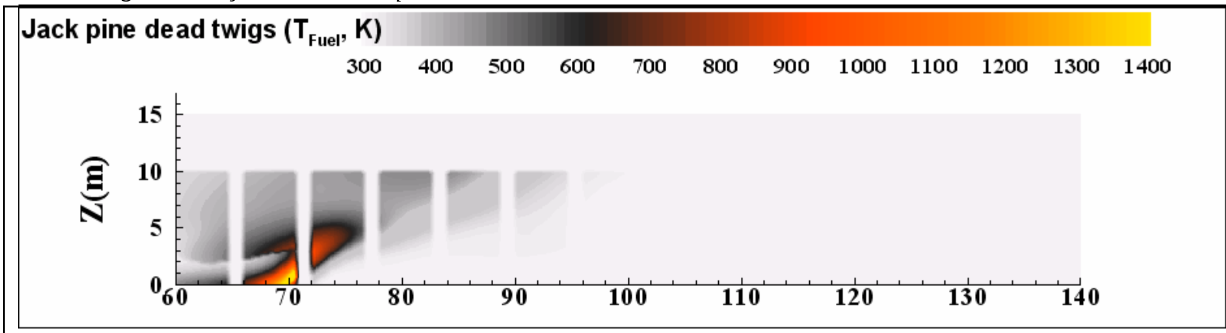

FIG. 3: Temperature fields calculated at the same time, in the gas, in the foliage, in the twigs (leaving and dead), during the propagation of a fire through a boreal forest.

Conclusions

The behaviour of forest fires was simulated using a multiphase formulation. The present model included the main physical mechanisms contributing to the propagation of a fire through a vegetation layer: decomposition of the vegetation (by drying and pyrolysis) under the intense heat flux released by the fire front, transport and combustion of pyrolysis gas, radiation coming from soot particles in the flame and from vegetation (charcoal and ashes). Results obtained for a crown fire were compared with experimental data collected during experimental campaign carried out in boreal forest in Canada.

References

[1] Morvan D., Dupuy J.L.. Modelling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation. *Combustion & Flame*, 138: 199-200, 2004.

[2] Linn R., Reisner J., Colman J.J., Winterkamp J.. Studying wildfire behaviour using FIRETEC. *Int. J. Wildland Fire*, 11: 233-246, 2002.

[3] Mell W., Jenkins M.A., Gould J., Cheney Ph.. A physics-based approach to modelling grassland fires. *Int. J. Wildland Fire*, 16(1): 1-22, 2007.

[4] Morvan D., Méradji S., Accary G.. Physical modelling of fire spread in Grasslands. *Fire Safety Journal*, 44: 50-61, 2009.

[5] Morvan D., Méradji S., Accary G.. Wildfire behaviour study in a Mediterranean pine stand using a physical based model. *Combustion Science and Technology*, 180(2): 230-248, 2008.

[6] Modest M.F.. Radiative heat transfer. Academic Press, 2nd Edition, 2003.

[7] Stocks B.J., Alexander M.E., Lanoville R.A.. Overview of the International Crown Fire Modelling Experiment (ICFME). *Canadian J. Forest Research.* 34: 1543-1547, 2004.Raupach M.R., Bradley E.F., Ghadiri H., 'A wind tunnel investigation into aerodynamic effect of forest clearings on the nesting of abbott's Boody on Christmas Island. Internal report, CSIRO Centre for environmental Mechanics, Canberra, pp. 21, 1987.