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Numerical simulation of live chaparral fire behavior using FIRETEC

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Abstract

Fire spread through chaparral fuels is a significant feature of wildland fire in southern California. In order to study the detailed physical processes involved during fire spread, FIRETEC, a coupled atmosphere/wildfire behavior model was refined to examine chaparral fire behavior. FIRETEC combines a sophisticated fine-scale model to simulate a three-dimensional wildfire, moving over a terrain-following finite volume grid, with the motions of the local atmosphere. It accounts for the microscopic details of a fire with macroscopic resolution by dividing quantities into mean and fluctuating parts and the resulting transport equations are solved by using a finite difference method. In this paper, fire spread through live chaparral fuels under different burning conditions was studied. Specifically, the effect of varying environmental variables and physical characteristics of fuels on fire spread was examined. Results from four simulations are presented. They demonstrate the effects of wind speed in enhancing heat transfer from the fire to unignited fuel ahead of the fire front. Increased fuel loading and packing ratio resulted in decreased rate of spread; while increased fuel moisture reduced the predicted rate of spread, consisted with our laboratory scale experiments.

Introduction

Fire burning in chaparral fuels is a significant annual event in California. Under extremely hot, dry, and strong Santa Ana wind, chaparral fires may rapidly burn thousands of hectares. Current operational models used for predicting the spread of fire are mainly based on statistical or semi-empirical formulations (McArthur 1966; Finney 1995; Rothermel 1972), and cannot explain the complex physical and chemical mechanisms that occur within a fire. Physics-based fire spread models (Albini 1967; Albini 1985; Albini 1986; Pagni and Peterson 1973) may potentially work well in chaparral but there is limited experimental data to develop and test them. In order to study interactions between the important processes within a chaparral fire, FIRETEC (Linn 1997), a coupled atmospheric transport/wildfire behavior model developed at Los Alamos National Laboratory, was refined to include some variation in live moisture and live chaparral fuel properties and applied to examine the effects of wind speed, fuel loading and moisture content of fuels on fire spread through chaparral. FIRETEC is based on a numerical solution of conservation of mass, momentum, species, energy, and turbulence equations and combines with a hydrodynamics model, HIGRAD (Reisner *et al.* 2000) to simulate a three-dimensional wildfire moving over a terrain-following finite volume grid with the motions of the local atmosphere. HIGRAD is ideal for representing the sharp temperature and flow gradients encountered in the vicinity of wildland fire. The model is second order in time and space and solved by a finite difference method. Combining these two models enables it to capture the combined effects of small micro-events on the macro-scale fire behavior by dividing quantities into mean and fluctuating parts and then taking ensemble averages of equations. The physically based self-determing nature makes FIRETEC a useful learning tool used to examine some complex wildland fire behaviors (variable wind conditions, non-homogeneous fuel terrain, non-uniform fuel bed with patchy distributions, and different vertical fuel structures).

As the chaparral fire spreads successfully at higher fuel moisture (>60%) than most of experimental data used to develop Rothermel model (<30%) for no wind and flat ground condition, we embarked on a study of fire spread through a chaparral (*Adenostoma fasciculatum*) fuel bed under a variety of burning conditions (different wind conditions, fuel moisture, and fuel loading). By analyzing physical processes involved in fire propagation of live chaparral fuels associated with these burning conditions, we were able to understand the effect of some important physical properties of fuel and environmental variables that determine fire propagation.

FIRETEC model

Details of the numerical model formulation are described in Linn (1997), Reisner *et al*. (2000), and Linn *et al*. (2002) and are not repeated here. Four simulations were carried out in an attempt to understand the effects of physical characteristics of fuels and environmental variables on chaparral fire propagation. As a baseline case, a fuel loading (dry mass per unit of fuel bed area) of 2.29 kg/m^2 and packing ratio (ratio of fuel volume to fuel bed volume) of 0.0043 was considered in simulation 1. The ambient wind is imposed as a boundary condition on the left side of the domain at 3 m/s. The moisture content (ratio of water mass to dry fuel mass) of the fuel was set as 50% initially. This value represents live chaparral fuel moisture during a typical fire season in California. Simulation 2 consists of a fire ignited in a larger domain compared to simulation 1 with the ambient wind speed increased to 6 m/s and held constant through the simulation. In simulation 3, the initial moisture content is increased to 90% to simulate live chaparral in typical prescribed fire season, while in simulation 4 the fuel loading is increased to 4.58 kg/ m^2 and packing ratio doubled to 0.0086 with all other conditions identical to the fire in simulation1. The fuel bed characteristics chosen include the initial height of the fuel bed of 0.8 m, the surface area to volume ratio of 4000 m^{-1}, a heat of combustion of 8914 kJ/kg, and a fuel particle density of 662 kg/m^3 (Countryman *et al.* 1970).

Each of the simulations was run for 300 s. In simulation 1, 3 and 4, the computational domain is a rectangular box of size 80 × 80 × 42 m, while in simulation 2 the domain size changed to 120× 80 × 42 m in order to provide more room for the fire to progress under higher ambient wind speed. The horizontal grid spacing is uniform at 2 m, while the vertical grid spacing is stretched with the smallest size of 1.5 m near the ground. The homogenous fuel is distributed only in the layer nearest the ground. The chaparral is ignited in the ignition zone within a 4 × 10 m box (see Fig.1) by removing any fuel moisture and steadily raising the mean temperature of the fuel from 300 K to 500 K over 1 s.

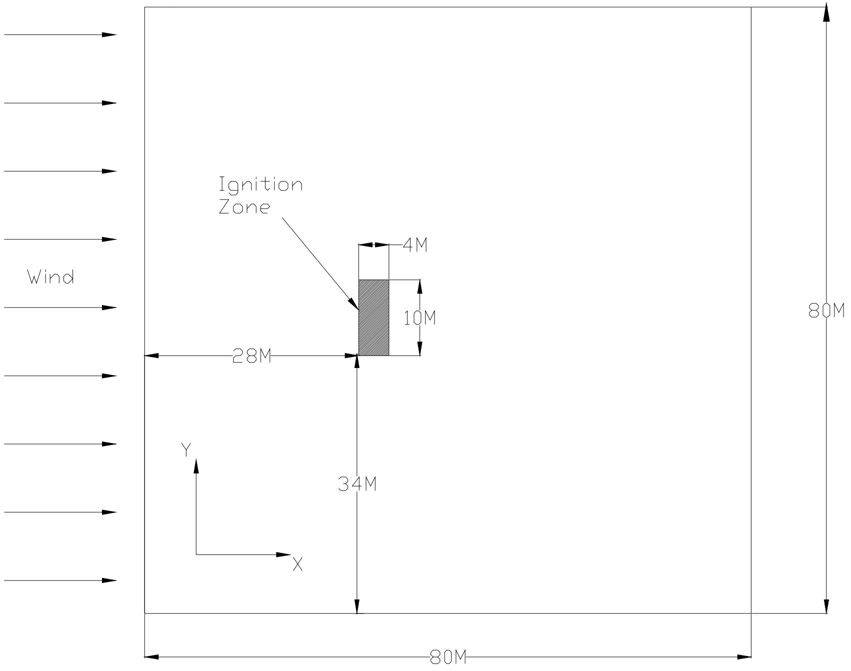

Fig.1. Basic layout of the simulation 1 at the time of ignition.

Results

The results presented in all figures show potential temperature and the bulk ground fuel density. The gray to yellow color represents the potential temperature from low to high. The deep green color indicates initial fuel density, light green color means the moisture evaporation from the live fuel, and black color indicates fuel depletion. Fig.2 and Fig.3 show the results from simulation 1 at 150 s and 300 s respectively. As time progresses, the fire propagates from its initial ignition zone to downwind direction and the fire perimeter becomes irregular and wider because of the interaction of the fire and the atmosphere. More and more fresh air is entrained into the fire plume which accentuates fire propagation. Fig.4 shows the fire in simulation 2 at 300 s. Comparing Fig.3 with Fig.4, we can easily see that the increase of the ambient wind speed from 3 m/s to 6 m/s causes the fire to lay over in the downwind direction and much of the plume remains closer to the unburned fuel. The re-circulation of hot gases helps preheat the unburned fuel ahead of the fire front and accelerate fire propagation. In wind-driven fires, convective heat exchange is increased and plays a more important role in heating unignited fuel. The eventual spread rate of the fire in simulation 2 in the positive *x* direction is approximately 0.10 m/s, which is faster than the spread rate in simulation 1 of 0.09 m/s. The fire in simulation 2 is still accelerating, so we expect the spread rate would be even higher at later time. This spread rate is slower than that of 0.11 m/s measured by Chandler (1963) under the same ambient wind speed but at low moisture content of 4% for brush fuels.

Fig.5 shows the fire behavior in simulation 3 at 300 s for an increased fuel moisture content of 90%. The eventual spread rate of fire in simulation 3 at 300 s is about 0.08 m/s. We see the fire is still propagating at 300 s, even though the descending trend indicates fire propagating at slower rate gradually and the isosurfaces of temperature are lower than that in simulation 1 and simulation 2. These results demonstrate that under the same circumstances, the fuel with high moisture propagates at a slower rate because it is losing energy to moisture evaporation. As we observed in lab-scale marginal burning experiments (Weise *et al.* 2005, Zhou *et al.* 2005), wind plays a more important role in fire propagation than fuel moisture. With the aid of wind, even with high fuel moisture the fire can still propagate successfully. Calculated results agree qualitatively with our experimental observations. Fig.6 shows fire in simulation 4 at 300 s (with higher fuel loading and higher packing ratio) progressing slower (0.008 m/s) than fire in simulation 1. This is because increasing fuel loading and packing ratio results in more fuel compacted in the fuel bed, which restricts fresh air flow into the fuel bed and the oxygen supply is hence deficient. The result is consistent with the conclusion of Countryman *et al.* (1970).

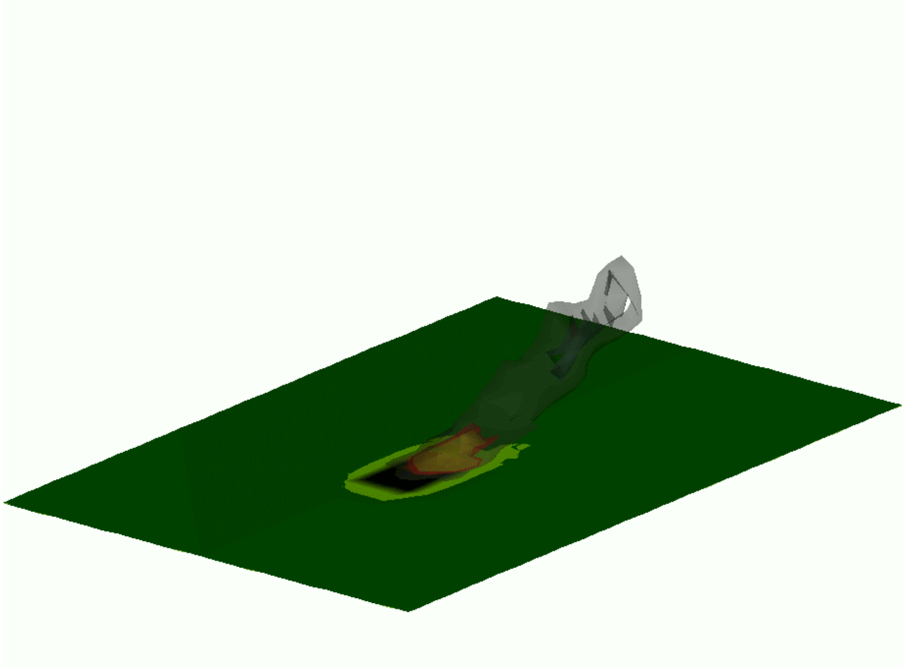

Fig.2 Fire propagation in a base line case (simulation 1) at 150 s. The yellow, red, and gray isosurfaces represent regions in which the potential temperature is above 600 K, 500 K and 350 K respectively. The horizontal surface color contour indicates fuel density variation, the darker the color, the less fuel remains at that location.

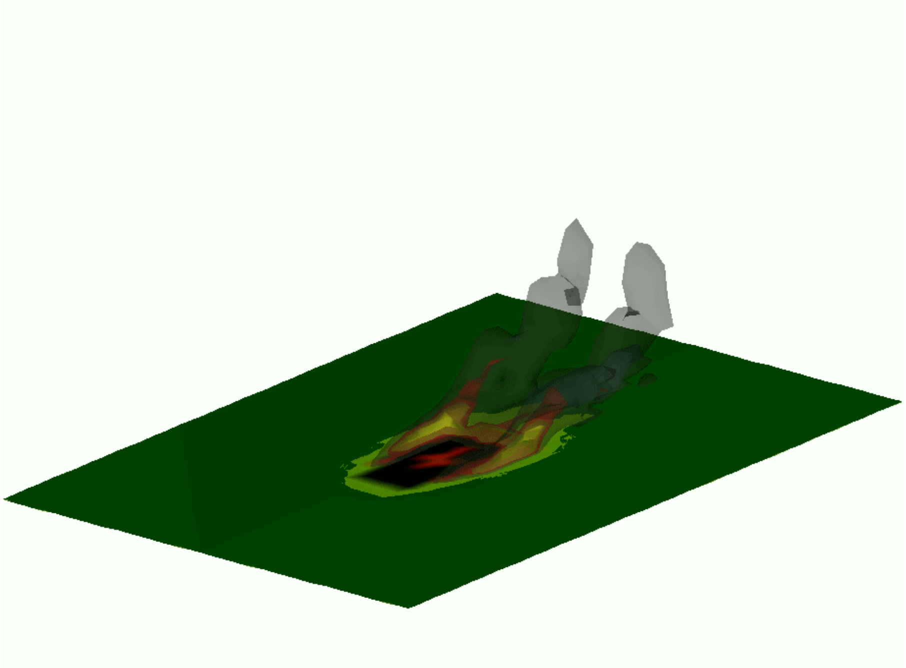

Fig.3 Fire propagation in a baseline case (simulation 1) at 300 s. The yellow, red, and gray isosurfaces represent regions in which the potential temperature is above 600 K, 500 K and 350 K respectively. The horizontal surface color contour indicates fuel density variation, the darker the color, the less fuel remains at that location.

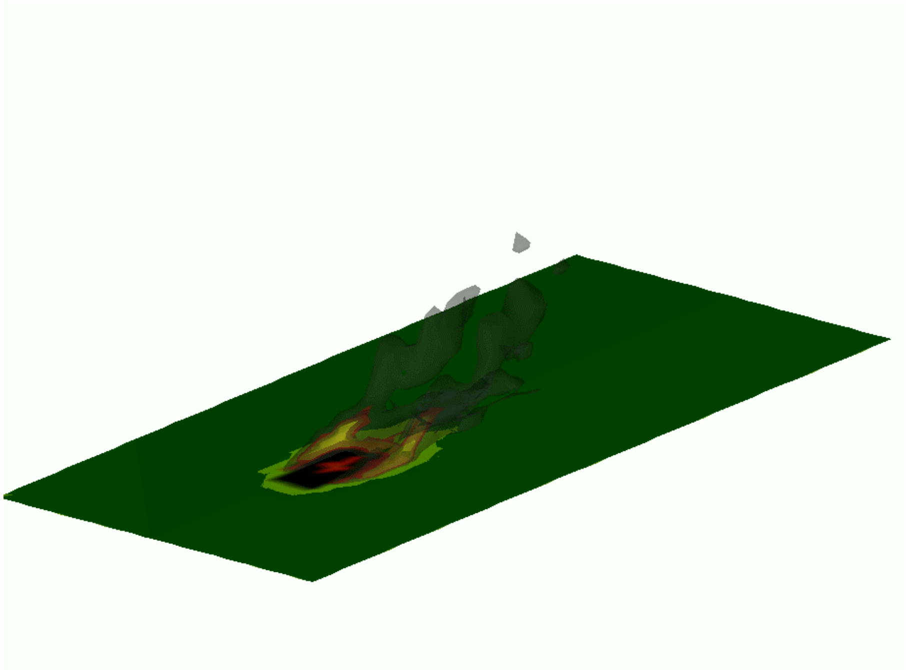

Fig.4 Fire propagation in simulation 2 at 300 s with high wind speed in a larger domain after ignition. The yellow, red, and gray isosurfaces represent regions in which the potential temperature is above 600 K, 500 K and 350 K respectively. The horizontal surface color contour indicates fuel density variation, the darker the color, the less fuel remains at that location.

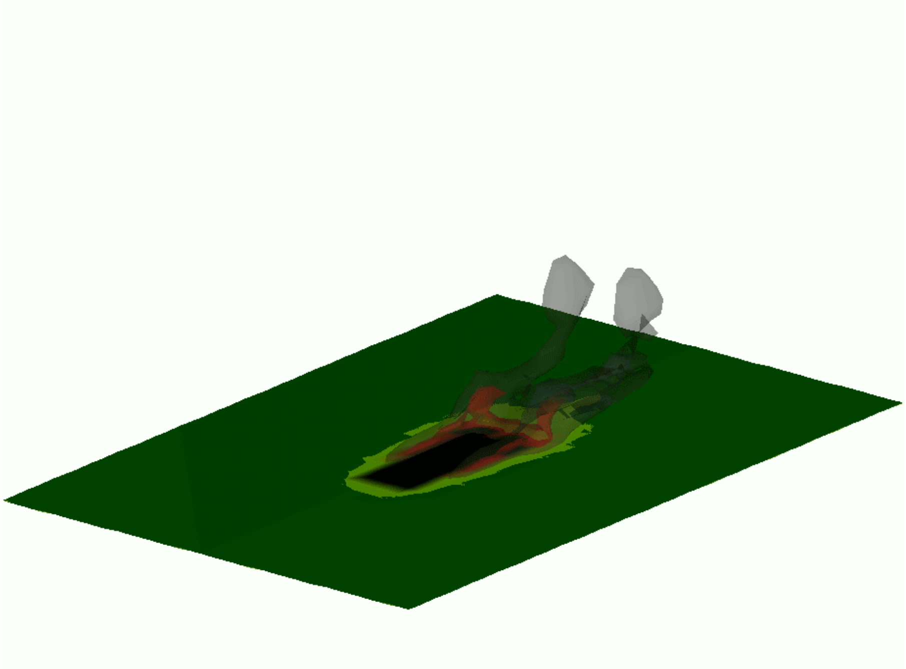

Fig.5 Fire propagation in simulation 3 at 300 s with high fuel moisture content after ignition. The yellow, red, and gray isosurfaces represent regions in which the potential temperature is above 600 K, 500 K and 350 K respectively. The horizontal surface color contour indicates fuel density variation, the darker the color, the less fuel remains at that location.

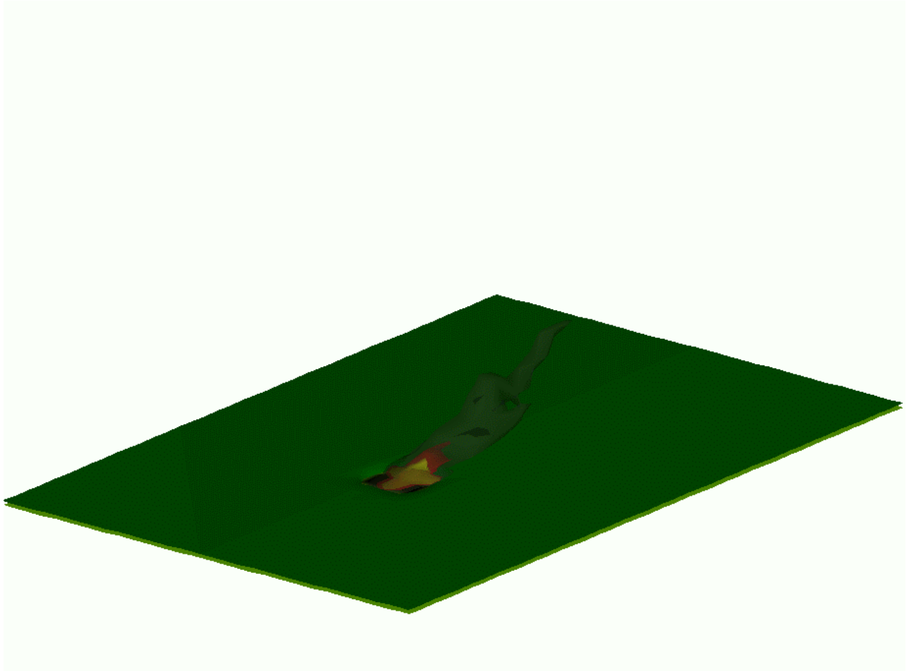

Fig.6 Fire propagation in simulation 4 with high fuel loading at 300 s after ignition. The yellow, red, and gray isosurfaces represent regions in which the potential temperature is above 600 K, 500 K and 350 K respectively. The horizontal surface color contour indicates fuel density variation, the darker the color, the less fuel remains at that location.

Summary and Future Research

Fire spread through live chaparral fuels was simulated by using a physics-based wildfire model. By studying the driving physical processes through four simulations, we observed the wind-driven fire is controlled mostly by convection as the flame lays over in the downwind direction due to the change of wind speed. Heated air is carried downwind which helps ignition of unburned fuel and increase fire spread rate. Wind speed plays a more important role in fire propagation than fuel moisture content. Fire can propagate at high fuel moisture with the assistance of wind. Under the same circumstances, given fuel with high moisture content, fire propagates at a slower rate, while increased fuel loading and packing ratio result in a decreased spread rate. The simulation results are not unexpected or novel but the use of physical-based full-transport model provide us a new avenue to better understand wildfire behavior in California from unique physical characteristics of fuels and landscape. More work is also needed for interpreting model performance on chaparral fuels for complex environments associated with various wind conditions.

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