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Progress in Modeling Wildland Fires using Computational Fluid Dynamics

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Abstract: This paper presents a sensitivity study for computational fluid dynamics (CFD) simulations of grassland fires. The simulations are compared with prescribed burns conducted in northern Australia in 1986. The researchers who conducted these burns noted that wind speed and moisture content are the most important factors determining the spread rate of the fire front. These and various other physical and numerical parameters in the model are varied to determined their relative importance in the simulation.

***Keywords:* Computational Fluid Dynamics, Fire, Wildfire**

1. Introduction

Computational fluid dynamics (CFD) is routinely used to study the spread of smoke and fire in buildings [1], and over the past decade it has become increasingly used to study wildland fires. The primary challenge in modeling wildfires is characterizing the burning vegetation. A popular method for representing leaves, twigs, grasses, etc., is via Lagrangian particles, as described by Mell *et al.* [2] and Morvan and Dupuy [3]. These particles serve as subgrid-scale sources and sinks of mass, momentum, and energy on computational grids that span hundreds to thousands of meters. The advantage of using particles to represent the vegetation is that they are less sensitive to grid resolution. Unless an adaptive meshing scheme is used, simulations of fire spread over hundreds or thousands of meters can only be done on computational grids with cells on the order of meters.

The challenge of this type of modeling is that there are a seemingly infinite variety of vegetation and geometric configurations to consider. However, given the uncertainties in all other parameters, it might be a reasonably good approximation to consider bulk vegetation to be a composite of water and cellulose. What "reasonably good" means will depend on the application, but what has been learned from the extensive modeling of building fires is that the exact composition of the fuel and its combustion products is not as important as once thought. That is to say, it is possible to simulate the impact of a fire on a building without knowing the detailed composition of the fuel molecule, in either solid or gaseous form.

2. Model Description

A complete description of the Fire Dynamics Simulator (FDS) is given in Ref. [4] and additional details of how vegetation is treated are given in Ref. [2]. Briefly, FDS is a computational fluid dynamics (CFD) model of fire-driven flows. The model numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The partial derivatives in the conservation equations for mass, momentum, and energy are approximated by finite differences, and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Lagrangian particles are used to simulate sprinkler droplets, fuel sprays, and unresolvable subgrid-scale objects. In particular, individual blades of grass are modeled as slender cylinders whose diameters are inferred from the measured surface area to volume ratio, σ. By applying appropriate weighting factors, one explicitly modeled blade of grass represents hundreds or thousands of actual blades. It is assumed that the blades are rigidly fixed and perpendicular to the wind and the source of thermal radiation. Empirical heat transfer and drag coefficients are applied. There is no accounting for the effect of "shadowing"; that is, the fact that the drag coefficient should be reduced due to the effect of upwind obstructions.

The impact of all of these assumptions on the rate of spread of the fire is difficult to determine other than by sensitivity analysis. Before embarking on developing a more detailed model of the blade of grass, it is important to gauge the impact of the various physical parameters that describe the simple model.

3. Results and Discussion

In July and August of 1986, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia conducted controlled burns in grasslands near Darwin, Northern Territory [5]. July and August are in the middle of the dry season when the grasses are fully cured (dried) and the weather is warm and dry. Two of these burns were simulated with FDS by Mell *et al.* [6] and are discussed here. Case C064 was conducted on a flat 100 m by 100 m plot of kerosene grass (*Eriachne burkittii*); Case F19 was conducted on a flat 200 m by 200 m plot of kangaroo grass (*Themeda australis*).

Measured properties for the specific types of grassesmc are listed in Table 1. Assuming that the blades of grass are cylindrical, the diameter is calculated from the surface area to volume ratio, $\sigma = 4/D$. The grass height and bulk mass per unit area yield the bulk density of vegetation within the first one or two grid cells above the ground. The moisture is assumed to be water.

Table 1: Measured properties for the CSIRO Grassland Fire cases [5].

Property	**Units**	**Case F19**	**Case C064**
Wind Speed at 2 m height	m/s	4.8	4.6
Ambient Temperature	°C	34	32
Surface Area to Volume Ratio	m^{-1}	12240	9770
Grass Height	m	0.51	0.21
Bulk Mass per Unit Area	kg/m^2	0.313	0.283
Moisture Fraction	%	5.8	6.3

Properties that were not measured are listed in Table 2. These assumed properties are typically for wood or cellulosic fuels. The grass is assumed to be composed primarily of cellulose and

Table 2: Assumed properties for various types of dried grass and soil. Note that the Pyrolysis Temperature is taken to be the temperature at which the mass loss rate peaks in the TGA experiments of Morvan and Dupuy [3].

Property	**Units**	**Value**	**Reference**
Gas Phase Combustion Parameters			
Chemical Composition	–	$C_6H_{10}O_5$	Assumption
Heat of Combustion	kJ/kg	15600	[7]
Radiative Fraction	–	0.35	Assumption
Soot Yield	kg/kg	0.015	[8]
Vegetation Parameters			
Char Yield	kg/kg	0.2	[7]
Specific Heat	kJ/(kg·K)	1.5	Assumption
Conductivity	W/(m·K)	0.1	Assumption
Density	kg/m^3	512	[9]
Heat of Pyrolysis	kJ/kg	418	[3]
Pyrolysis Temperature	°C	200	[3]
Soil Parameters			
Soil Specific Heat	kJ/(kg·K)	2.0	[10]
Soil Conductivity	W/(m·K)	0.25	[10]
Soil Density	kg/m^3	1300	[10]

water. The various other parameters are selected from the literature, and even those that are based on measurements of vegetation are not necessarily for grasses. For this reason, the sensitivity of these parameters shall be studied.

A snapshot of the simulation of Experiment C064 is shown in Fig. 1. The version of FDS is 6.5.3. The computational domain in this case is 120 m by 120 m by 20 m. The grid cells are 0.5 m cubes. The domain is subdivided into 36 individual meshes and run in parallel. The grass is represented by 40,000 Lagrangian particles with a cylindrical geometry, or one simulated blade per grid cell, positioned at the cell center. The radius of the cylinder is derived from the measured surface area to volume ratio. Each simulated blade of grass represents approximately 5000 actual blades of grass. This weighting factor is determined from the measured bulk mass per unit area. The fires in the experiments were ignited by two men carrying drip torches walking in opposite directions along the upwind boundary of the plot (the red strip in Fig. 1). In FDS, this action was modeled using a specified spread rate along the strip. The 120 s simulation requires about 40 min of wall clock time. A more finely resolved calculation (0.25 m cells) requires about 11 h. A crude calculation (1 m cells) requires about 4 min. While the rate of spread of the fire front varies only about 5 % over this range of grid resolution, there is considerably more variation in the behavior of the flanking (side) fires or fires subjected to very low wind speeds. In short, concurrent flow flame spread is less sensitive to grid size than opposed flow flame spread.

The measured rates of spreads of the fire front for cases C064 and F19 are 1.16 m/s and 1.46 m/s, respectively. The model, using best estimates of the parameters, predicts 1.37 m/s and 1.47 m/s, respectively. The close agreement in the case of F19 is purely coincidental given the

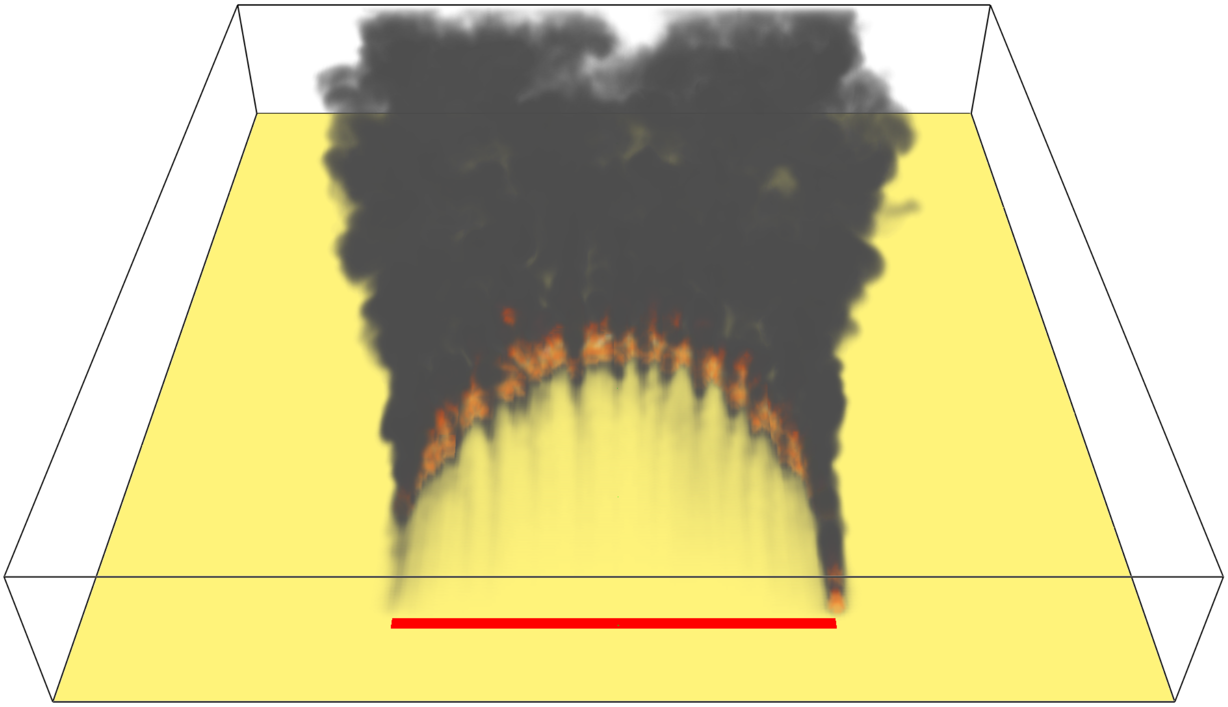

Figure 1: Snapshot of the simulation of CSIRO Grassland Fire C064. The computational domain is 120 m by 120 m by 20 m high. The red strip indicates where the fire was ignited.

uncertainty of all the parameters. To better understand which parameters have the largest impact on the results, a simple sensitivity analysis was performed for Case C064, in which selected parameters were varied one at a time. The condition number, c,

$$c = \frac{\Delta R/R}{\Delta x_i/x_i} \tag{1}$$

indicates the relative importance of parameter x_i on the rate of spread, R. These values are listed in Table 3.

Cheney *et al.* [5] noted that the key physical parameters determining the rate of spread of fire through flat grasslands is the wind speed and moisture content. In their analysis of the CSIRO experiments, they correlate the data in several different ways, but to a first approximation these correlations are all of the form

$$R = 0.5\,U_2\,\exp(-0.1\,M) \tag{2}$$

where U_2 is the wind speed measured at a height of 2 m and M is the moisture content of the grass, expressed as the percentage of moisture mass per unit mass dry vegetation.

While the model replicates reasonably well the effect of wind on the rate of spread, it does not capture the effect of moisture. Given the empirical relation in Eq. (2), the condition number for moisture ought to be $-0.1\,M$, which in this case is -0.63. Instead the model value is -0.09 (Table 3. In other words, the model is less sensitive to moisture content than the experimental data suggests. A possible reason for this is that the model assumes that the moisture is water that freely evaporates from the surface of the blade of grass. In reality, the process might be more complicated and not as easily described by the model.

Another significant parameter is the pyrolysis temperature. This parameter represents the temperature at which the mass loss rate is at its peak, based on TGA (thermo-gravimetric analysis) measurements made by Morvan and Dupuy [3] for a variety of different types of vegetation, none of which were Australian grasses. Obviously, this parameter plays an important role in the pyrolysis routine. Other thermo-physical parameters of the grass are less important, such as its specific heat, density, heat of pyrolysis, bulk mass per unit area, and assumed diameter.

The radiative fraction assumed in the model, 0.35, is a specified fraction of the fire's energy that is assumed to be emitted as thermal radiation, as opposed to the heat that is drawn into the smoke plume. Although this parameter has not been measured for this type of vegetation, a wide variety of common materials fall in the range of 0.3 to 0.4 [8]. This choice of 0.35 did not significantly affect the rate of spread.

One parameter not listed in Table 3 is the number and position of the Lagrangian particles that represent the grass. Mell *et al.* [2] recommend that one particle be centered in each computational grid cell, which has been done in the base case here, but one could also randomly distribute the particles to mimic reality. This was done as well, in which case the centroid of the simulated blades of grass were positioned roughly 10 cm off the ground, half the height of the cut grass. Changing the particle location from its original centered position, 25 cm off the ground, to the assumed grass mid-point height, 10 cm off the ground, led to a 7 % increase in the front speed. The reason for the change in front speed is due to the change in drag coefficient caused by the change in wind speed that is linearly interpolated from the 50 cm gas phase grid.

Table 3: Results of the sensitivity analysis. A positive Condition Number indicates that an increase in the given parameter leads to an increase in the fire's rate of spread.

Parameter Name	**Best Estimate**	**Lower Bound**	**Upper Bound**	**Condition Number**
Wind Speed (m/s)	4.6	3.0	6.0	1.01
Moisture (%)	6.3	3.2	9.5	-0.09
Pyrolysis Temperature (K)	473	423	523	-0.53
Specific Heat, Grass (kJ/(kg·K)	1.5	1.0	2.0	-0.05
Radiative Fraction	0.35	0.30	0.40	0.02
Blade Diameter (mm)	0.4	0.2	0.6	-0.08
Bulk Mass per unit Area (kg/m^2)	0.283	0.142	0.425	0.02
Heat of Pyrolysis (kJ/kg)	418	334	502	-0.06
Grass Density (kg/m^3)	512	410	614	-0.06

4. Conclusions

A sensitivity study has been conducted to determine the relative importance of physical and numerical parameters governing the simulation of fire spread through flat grasslands. In terms of physical parameters, the wind speed and moisture content are the most important, and the model captures well the effect of the former but not the latter. The experiments revealed a more significant dependence of moisture content on the rate of spread than the model, suggesting that the simple handling of moisture may not adequately address this phenomenon. The most important numerical parameter is the assumed position of the centroid of the simulated blade of grass relative to the ground, which had a more pronounced impact on the rate of spread than the experiments indicate, based on comparing similar experiments that had different grass cut heights.

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