5.4 NUMERICAL MODELING OF FIRE SPREAD THROUGH INDIVIDUAL TREES AND SHRUBS

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1. Introduction

Fire spread through suspended vegetation, such as tree crowns and shrubs, is a basic component of wildland fires. Most models of fire spread through tree crowns do not resolve the burning of individual trees. Instead, these models are developed for, and limited to, fire spread through a forest canopy, representing a collection of tree crowns in an average sense (fore example, Bulter et al. [2004]). There are a number of fire problems, however, where an understanding of fire spread through one or a number of trees or shrubs is needed. Among these fire problems are: the effect of a fire on tree health, the influence of a given fuel treatment on fire intensity, and fire spread through the intermix of vegetation and structures in the wildland-urban interface (WUI). The National Institute of Standards and Technology (NIST) currently has an experimental and modeling project that seeks to improve our understanding of WUI fires. In this talk measurements from laboratory experiments of burning vegetative fuels (idealized shrubs and actual trees) will be compared to results of a three-dimensional, physics based, computer simulation model currently under development at NIST. The end use of this model is to predict the behavior of fires and assess fire risk in the wildland-urban interface.

2. Numerical Simulation Approach

The computer simulation tool used here is called WFDS (Wildland-urban-interface Fire Dynamics Simulator) and is an extension, to vegetative fuels, of NIST's three dimensional, time dependent, structural fire simulation code FDS (Fire Dynamics Simulator) (McGrattan [2004]). The development of FDS started in the 1980's with the objective of creating a computationally efficient CFD based simulation tool for structural fires. FDS can be run on single processor desktop computers or on multiple processors and on a range of operating systems. It is currently used worldwide by 100s of fire protection engineers for structural fires and can be downloaded free. Smokeview, a companion software package, was also developed at NIST to interactively visualize FDS results (Forney and McGrattan [2004]). A survey of FDS validation studies is given in McGrattan [2004].

Recently, modifications to FDS were begun to handle fire spread through vegetative fuels (Rehm et al. [2003], Mell et al. [2005a]) with the goal of simulating fire spread in an intermix of vegetative and structural fuels (i.e., WUI fires). The solution of the governing equations is based on basic Large Eddy Simulation concepts as first presented by Smagorinksy [1963]. The approach does not result in additional closure equations. A low Mach number approximation to the governing equations is used (Rehm and Baum [1978]). This approximation, which has been applied successfully to a wide range of fire and combustion problems, and the use of a fast direct solver for the pressure, results in computational speeds that are 10 to 100 times faster than many other methods, while retaining a high level of accuracy.

Gas phase combustion is modeled with the well established mixture fraction based approach that assumes the fuel and oxygen react instantaneously over time scales characteristic of the flow (Bilger [1980]). Thermal radiation transfer is computed with a finite volume based solver (Raithby and Chui [1990]). Details of governing equations and the numerical methods for the the gas-phase can be found in McGrattan [2004]. In the burning of vegetative fuels a physics based approach, in which all modes of heat transfer (radiative, convective, conductive) are directly modeled. The numerical approach is capable of simulating fire behavior over a large range of physical scale. For example, a model for surface fuel was recently developed and applied to fire spread in grassland fuels over a much larger overall domain (1500 m $\times$ 1500 m $\times$ 200 m; Mell et al. [2005b,a]) than the domains considered here.

This paper presents some results from the first stage of a model for the burning of vegetative fuel that has a three-dimensional structure and is raised above ground level. In such fuels, fire spread in the vertical direction can not be neglected. Vegetative fuel elements are assumed to be thermally thin. These fuel elements (e.g., needles of cross section $\mathcal{O}(1\text{ mm})$) are unresolved on the computational grid which has cell dimensions of 2.5 cm to 15 cm on a side. Mass, momentum (i.e. drag), and radiative interaction of the subgrid fuel elements is based on a modeling approach developed for

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sprinkler droplets (applied for fire suppression) in FDS (McGrattan [2004]).

3. Idealized shrub burns

Dupuy et al. [2003] created a laboratory apparatus that simulates the burning of an isolated shrub. Cylindrical wire-mesh baskets (of diameter 20 cm, 28 cm, and 40 cm) containing either Pinus pinaster needles or excelsior were used. Only numerical simulations of Pinus pinaster solid fuel have been conducted to date. For this reason only solid fuel parameters for Pinus pinaster will be given here. The numerical simulation required the following measured properties of the needles: bulk density (constant across basket diameters), 20 kg m^{-3}; surface-to-volume ratio, 4100 m^{-1}; density, 640 m^{-3}; moisture, 0.02 (moisture weight divided by dry fuel weight); low heat of combustion of the volatiles, Δh_{c} = 16 MJ kg^{-1}. In the experiments, ignition of the solid fuel was obtained by placing a ring shaped alcohol burner, with a 20 cm outer radius and a 18.5 cm inner radius, 1 cm beneath the bottom of the basket. A thermocouple tree was placed above the top of the basket. Vertical gas velocities were estimated from cross-correlations of thermal the fluctuations.

A characteristic snapshot of a numerical simulation of the 40 cm diameter basket with Pinus pinaster needles is shown in Fig. 1. The domain size is 2 m $\times$ 2 m horizontally and 3 m high. The computational grid is uniform with a cell size of 2.5 cm. Figure 1(a) is at an early, preignition time, of $t = 0.5$ s. The experimental ignition procedure was approximated by a placing a hot ring of similar dimensions and location to the alcohol burner used in the experiments (as much as allowed by the computational grid resolution). This ring was held at 800 ^{o}C for 10 s (the approximate burn time of the alcohol burner). In Fig. 1(a) this ring is red and is below the cylindrical volume containing the pine needles which is blue. Figure 1(b) is a snapshot of the burning needles at t = 40 s. Both the smoke plume and fire (visualized as a heat release rate isosurface) are shown.

Experimental and simulated heat release rates (HRR) (kW) are plotted in Fig. 2 for two basket diameters: 20 cm and 40 cm. Symbols are the experimental results. The solid line in Fig. 2 is the HRR determined by the mixture fraction based combustion model. This HRR is

$$\dot{Q}_{\mathsf{comb}} = -\int \sum_i h_i \dot{m}_i''' dV, \qquad (1)$$

where h_i is the specific enthalpy of gas species i, $\dot{m}_i'''$ is the mass consumption rate per unit volume of gas species i, and the integral is over a volume encompassing the fire. The dotted line in Fig. 2 is the HRR determined by multiplying the rate at which fuel gases are generated by pyrolysis ($\dot{m}_{\mathsf{pyr}}$) by the heat of combustion

$$\dot{Q}_{\mathsf{pyr}} = \dot{m}_{\mathsf{pyr}} \Delta h_{\mathsf{c}} \qquad (2)$$

As the fuel gases leave the surface of the vegetative fuel they rise and mix with air entrained by the fire plume and are ultimately consumed in the flaming region of the fire. If the fuel gases are completely consumed in the combustion process (which is an assumption of the model) then $\dot{Q}_{\mathsf{pyr}} \approx \dot{Q}_{\mathsf{c}}$. For a steady laminar flame, such as a gas burner, $\dot{Q}_{\mathsf{pyr}}$ equals $\dot{Q}_{\mathsf{c}}$. This is a basic validation check of any fire spread model that accounts for both solid phase thermal degradation (i.e., pyrolysis) and gas phase combustion. It ensures that the gas phase and solid phase are coupled properly, independently of whether or not the flame spread prediction is realistic. As seen in Fig. 2 WFDS does work properly in this respect. With regard to predicting experimental measurements, WFDS predictions of the heat release are too large initially and the duration of burning is too short. This could be related to the ignition process and is under investigation.

4. Tree burns

Experiments of burning Douglas fir are currently underway in NIST's large fire laboratory. Measurements of temperature, heat flux, heat release rate (HRR), and mass loss are being made. In addition, bioassays will be conducted to determine the fuel distribution in the tree crown. Since these experiments are not yet complete, experimental results reported here are from previous, exploratory, studies. In these previous experiments not all quantities required by the numerical model were measured. For this reason, results from these exploratory experiments are used here to evaluate the numerical model's ability to predict overall trends. As the current experimental effort produces more complete measurements the numerical model will be evaluated in more detail. Figure 3 shows a sequence of snapshots during the burning history, from both the experiment and the simulation, of a burning 2.4 m tall Douglas fir. The overall behavior of the fire as it spreads up and around the tree is reasonably well predicted by the numerical simulation.

Figures 4(a,b) are plots of the HRR versus time from the experiments and numerical simulation, respectively. Douglas firs of three different heights (H = 1.2 m, 2.4 m, and 3.6 m) were burned. The overall trend of increasing HRR with increasing tree height is reproduced by the simulation. Both the experiments and the simulation (with the exception of the shortest tree, H=1.2 m, in the case of the simulation) reached a

peak HRR at approximately 30 s. The decay of HRR with time occurs more slowly in the simulations.

In Fig. 5 the peak HRR (kW) plotted versus the moisture content (%). These results are for 2.2 m tall Douglas fir trees. The star symbols denote simulation results; the smaller open symbols are experimental values. The line is a curve fit through the experimental results reported by Babrauskas et al. [2002]. For the experiments two different ignition methods were used: (1) a small flame just below the branches of the Douglas fir, and (2) a surface fire throughout an area below the Douglas fir. In method (1) sustained burning of the tree did not occur for moisture contents above 55%; in method (2) burning did occur for moisture levels greater than 55%. The vertical line in the figure separates these two regions. Simulations using an approximation to ignition method (1) predicted extinction at moisture levels above 55%, in agreement with the experiments.

5. Conclusions

A three-dimensional time dependent model for fire spread through raised vegetation was applied to experiments in which idealized shrubs and Douglas firs were burned. The model is in its initial stage of development. Overall, predictions of heat release versus time and its dependence on tree size and moisture content were in reasonable agreement with experimental trends. With further development of the model and the completion of ongoing Douglas fir experiments a more thorough evaluation of the model will be conducted.

References

V. Babrauskas, G. Chastagner, and E. Stauss. *The SFPE Handbook of Fire Protection Engineering (Third Edition)*. National Fire Protection Association, 2002.

R.W. Bilger. *Turbulent Reacting Flows*, chapter 4. Turbulent Flows with Nonpremixed Reactants. Springer–Verlag, 1980.

B.W. Bulter, M.A. Finney, P.L. Andrews, and F.A. Albini. A radiation-driven model for crown fire spread. *Can. J. For. Res.*, 34:1588–1599, 2004.

J.L. Dupuy, J. Maréchal, and D. Morvan. Fires from a cylindrical forest fuel burner: combustion dynamics and flame properties. *Comb. Flame*, 135:65–76, 2003.

G.P. Forney and K.B. McGrattan. User's Guide for Smokeview Version 4: A Tool for Visualizing Fire Dynamics Simulation Data. Technical Report NISTIR Special Publication, 1017, National Institute of Standards and Technology, Gaithersburg, Maryland, August 2004. http://fire.nist.gov/bfrlpubs/.

K.B. McGrattan. Fire Dynamics Simulator (Version 4), Technical Reference Guide. Editor, McGrattan, K.B. NISTIR Special Publication, 1018, National Institute of Standards and Technology, Gaithersburg, Maryland, June 2004. http://fire.nist.gov/bfrlpubs/.

W.E. Mell, , M.A. Jenkins, J. Gould, and P. Cheney. A physics based approach to modeling grassland fires. *International Journal of Wildland Fire*, to be submitted, 2005a.

W.E. Mell, J.J. Charney, M.A. Jenkins, P. Cheney, and J. Gould. Numerical simulations of grassland fire behavior from the LANL-FIRETEC and NIST-WFDS models. EastFIRE Conference, May 11–13 2005b. George Mason University, Fairfax, VA.

G.D. Raithby and E.H. Chui. A Finite-Volume Method for Predicting Radiant Heat Transfer in Enclosures with Participating Media. *J. Heat Transfer*, 112(2): 415–423, 1990.

R. Rehm, D. Evans, W.E. Mell, S. Hostikka, K. McGrattan, G. Forney, C. Bouldin, and E. Baker. Neighborhood-Scale Fire Spread. page J6.7. American Meteorological Society, November 16-20 2003.

R.G. Rehm and H.R. Baum. The Equations of Motion for Thermally Driven, Buoyant Flows. *Journal of Research of the NBS*, 83:297–308, 1978.

J. Smagorinksy. General Circulation Experiments with the Primitive Equations I. The Basic Experiment. *Monthly Weather Review*, 91:99–164, 1963.

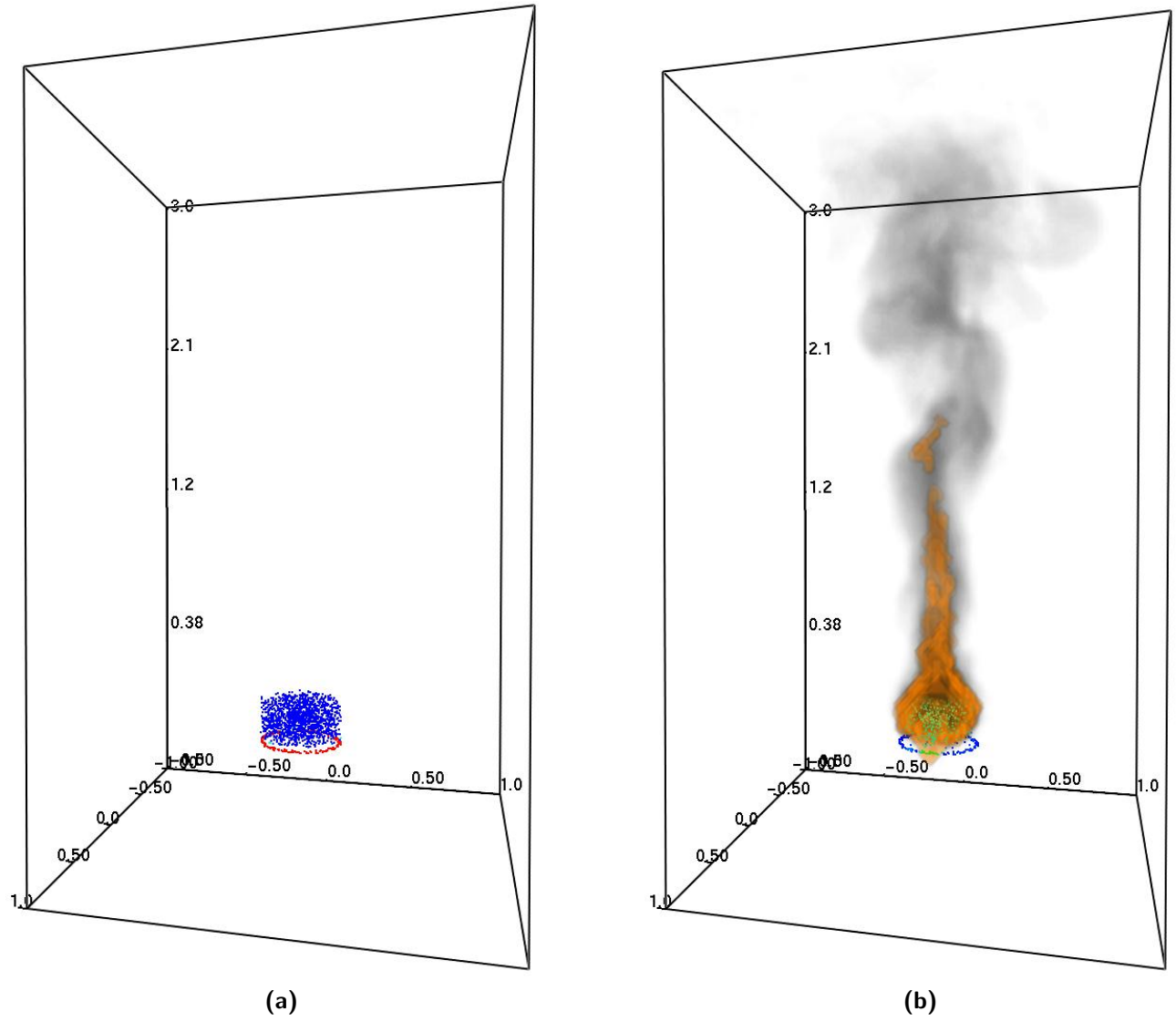

Figure 1: Snapshots of WFDS simulation of a cylindrical basket experiment (idealized shrub) of Dupuy et al. [2003]. The basket is 40 cm in diameter and 20 cm high and contains Pinus pinaster needles. **(a)** Before ignition of the needles; $t = 0.5$ s. The needles are colored blue. The red ring beneath the needles is held at 800 ^{o}C for 10 s to approximate the circular alcohol burner used in the experiments. **(b)** Snapshot later in time, $t = 40$ s, showing the smoke and fire plume. Note that consumption of the needles has occurred. The fire is visualized by a heat release rate isosurface (orange color).

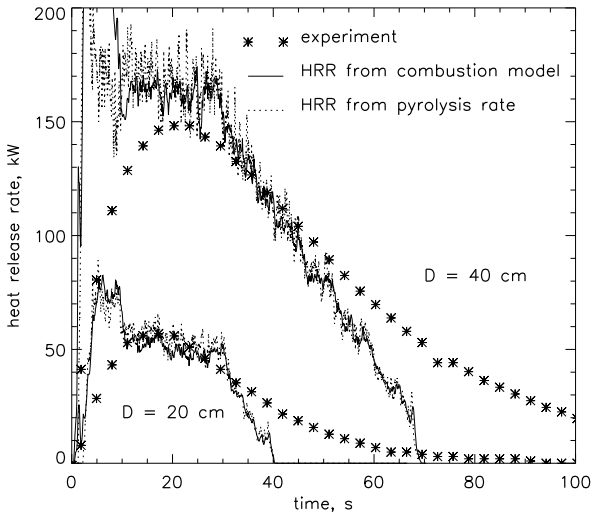

Figure 2: Heat release rate (HRR) versus time from the laboratory "shrub" burning experiments of Dupuy et al. [2003] and the numerical simulation WFDS. Symbols are experimental data and lines are the WFDS predictions. The heat release rates for two different shrub diameters are shown: $D = 20$ cm and 40 cm.

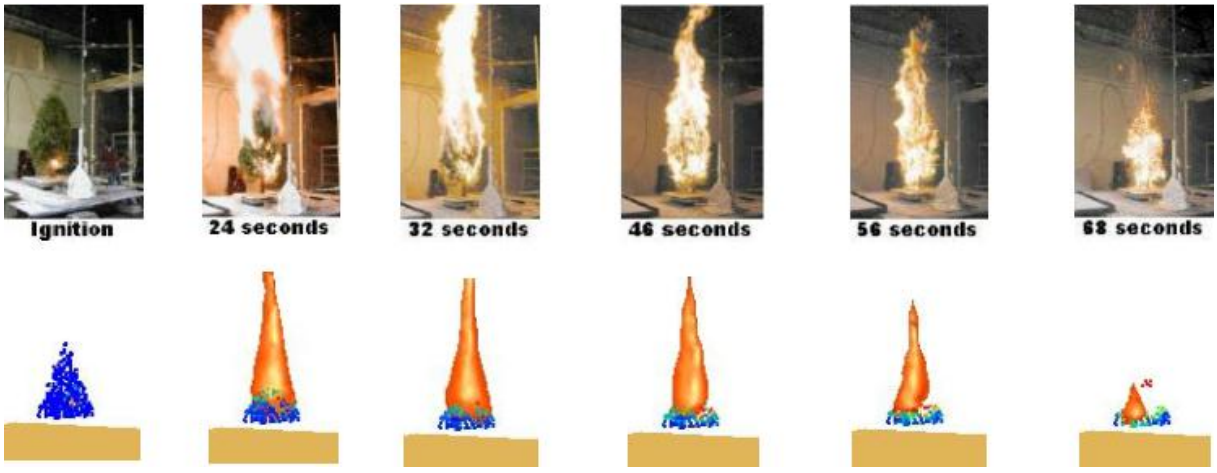

Figure 3: Snapshots of a burning 2.4 m tall Douglas fir tree in the laboratory (top row) and as simulated by WFDS (bottom row). The blues dots in the simulation represent the fine fuels in the tree canopy. They change color depending on their temperature. The fire is visualized with an isosurface of the heat release rate (orange surface).

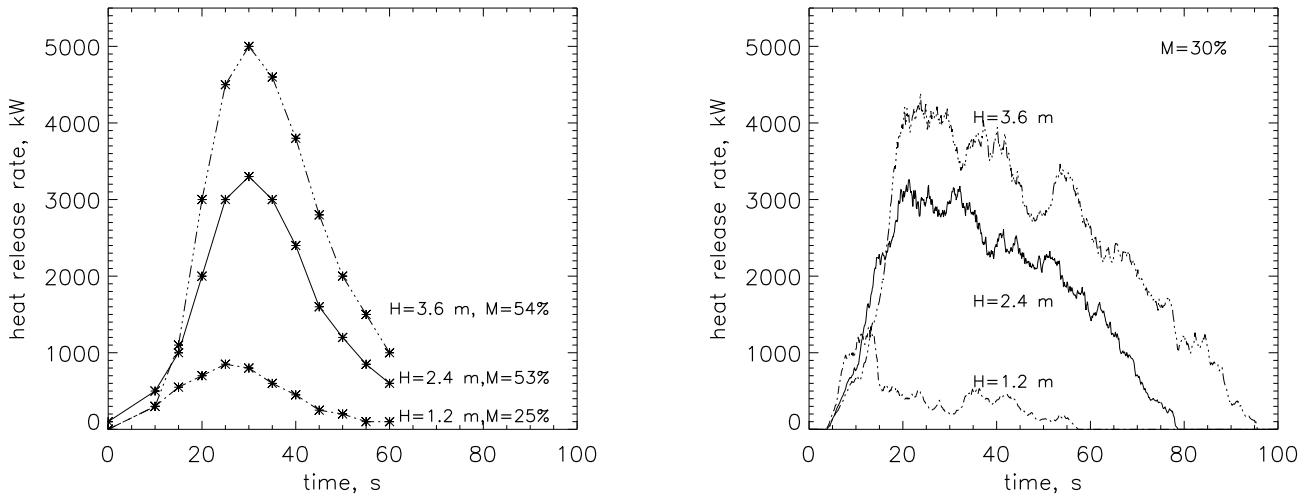

Figure 4: Heat release rate versus time for burning Douglas fir trees of three different heights: $H = 1.2$ m, 2.4 m, 3.6 m. **(a)** Measured values from experiments in NIST's large fire laboratory. **(b)** Predictions from WFDS of the heat release rate for the same sized trees. Note the moisture levels are 30% for all simulated trees but vary in the experiments. The overall trend of increased heat release with tree height is predicted.

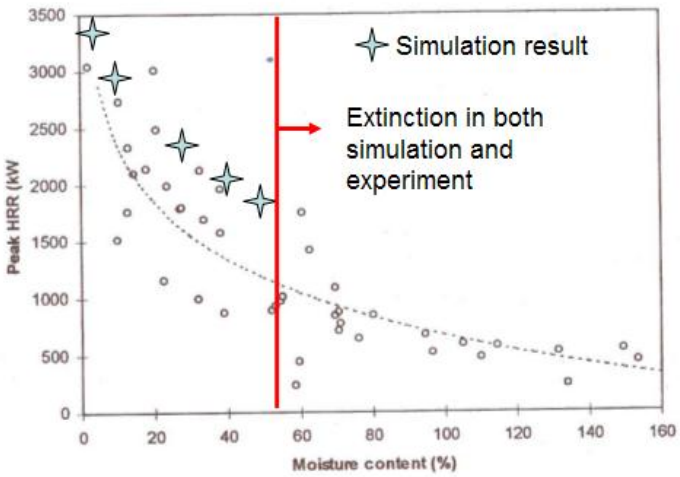

Figure 5: Peak heat release rate versus moisture content for burning 2.2 m tall Douglas fir. Stars symbols are from the numerical simulations; circles are from experiments. Experimental data is a compilation of experiments using two different ignition methods: localized flame or surface fire. For the localized flame ignition, sustained burning did not occur for moisture contents above 55%.