Examination of the Wildland-Urban Interface Fire Dynamics Simulator in Modeling of Laboratory-Scale Surface-to-Crown Fire Transition

Drew Castle¹, William E. Mell², Fletcher J. Miller¹

¹Department of Mechanical Engineering, San Diego State University, San Diego, CA 92812, USA
²Pacific Wildland Fire Sciences Lab, U.S. Forest Service, Seattle, WA 98103, USA

Abstract

Understanding the conditions leading to the transition of fire spread from a surface fuel to an elevated (crown) fuel is critical to effective fire risk assessment and management. Surface fires that successfully transition to crown fires can be very difficult to suppress, potentially leading to damages in the natural and built environments. This is relevant to chaparral shrub lands which are common throughout parts of the Southwest U.S. and represent a significant part of the wildland urban interface. The ability of the Wildland-Urban Interface Fire Dynamic Simulator (WFDS) to model surface-to-crown fire transition was evaluated through comparison to laboratory experiments. The WFDS model is being developed by the U.S. Forest Service (USFS) and the National Institute of Standards and Technology. The experiments were conducted at the USFS Forest Fire Laboratory in Riverside, California. The experiments measured the ignition of chamise (Adenostoma fasciculatum) crown fuel held above a surface fire spreading through excelsior fuel. Cases with different crown fuel bulk densities and imposed wind speeds were considered. Cold-flow simulations with WFDS yielded wind speed profiles that closely matched the experimental measurements. Next, fire simulations with only the surface fuel were conducted to verify the rate of spread while factors such as substrate properties and fuel moisture content were varied. Finally, simulations with both a surface fuel and a crown fuel were completed. Examination of specific surface fire characteristics (rate of spread, flame angle, etc.) and the corresponding experimental surface fire behavior provided a basis for comparison of the factors most responsible for transition from a surface fire to the raised fuel ignition. The rate of spread was determined by tracking the flame in the Smokeview animations using a tool developed for tracking an actual flame in a video. WFDS simulations produced results in both surface fire spread and raised fuel bed ignition which closely matched the trends reported in the laboratory experiments.

1. Introduction

The last decade in Southern California has brought about several of the most devastating wildland fires in the region’s history. The Cedar Fire in 2003, the Witch (Creek), Guejito, Harris, and other wildland fires in 2007 all brought a renewed focus to improving our understanding of how wildland fires ignite, spread, and interact with residential communities at the Wildland-Urban Interface (WUI) [3]. The native chaparral habitat which makes up a significant portion of the Southern California landscape [1] is also a major contributor of fuel to wildland fires in the area. Since it has already
been shown that fire behavior in wildland areas cannot be predicted by such singular factors as the percentage of dead fuel [7], improving our ability to model fire ignition and spread with live vegetation as a fuel source has become an important research area. The Wildland Fire Dynamics Simulator (WFDS) [2] program used in this study is being developed by the U.S. Forest Service (USFS) and the National Institute for Standards and Technology (NIST), and seeks to expand the scope of NIST’s existing Fire Dynamics Simulator (FDS) to include vegetation as a fuel. Here we seek to compare results from WFDS to experimental results to determine how accurately WFDS can predict flame rate of spread (ROS), crown fuel ignition, and other parameters with and without wind.

Tachajapong, et. al., in cooperation with the USDA Forest Service, performed a series of laboratory-scale experiments which examined the ignition of a crown fuel above a surface fire in varied conditions of vegetation density, imposed wind speeds, and crown elevation [9,10]. Crown fires which propagate through the elevated canopies of shrublands and coniferous trees can be extremely difficult to impossible to suppress under high wind and low fuel moisture conditions such as during Santa Ana events in southern California, and can spread much more rapidly than a surface fire [8]. Especially important for southern California, which is prone to Santa Ana conditions, is the effect of wind on the fire behavior. Wildland fires in these extreme environmental conditions can lead to destructive WUI fires [3]. Improving our understanding of the mechanisms by which this transition from a surface fire to a crown fire occurs, as well as our ability to predict and model these phenomena is an important focus of wildland fire research.

WFDS predictions have been compared to laboratory measurements of single burning trees [5] and Pinus Pinaster surface fires [6] and field measurements of Australian grassland fires [4]. There was reasonable agreement between WFDS predictions and measured quantities and trends. The current study is the first evaluation of the capability of WFDS to predict the failure or success of the transition fire spread in surface fuels to raised crown fuels in a laboratory setting. In particular, we determine the simulated ROS under conditions of no wind, and winds of 1.5 m/s, and 1.8 m/s both with and without crown fuel. The addition of the crown fuel is examined with different bulk densities.

2. Experimental and Computational Methods

2.1 Experimental Setup

The laboratory-scale experiments, which were conducted by the UC Riverside and Forest Fire Laboratory researchers used an aspen (Populus tremuloides) excelsior fuel bed with a depth of 10 cm and an overall area of 0.8 m wide by 1.8 m long in the direction of surface fire propagation (Figure 1). The excelsior fuel was placed on a substrate which was comprised of either solely Thermal Ceramics’ K23 fire brick in the experiments focused on the influence of bulk density on crown fire initiation, or a combination of the K23 fire brick and Kaowool fire board for experiments focused on the influence of wind speed on crown fire initiation. The physical properties for these substrates can be seen in Table 1.
The crown fuel used in these experiments was chamise (*Adenostoma fasciculatum*), the most prevalent species in southern California chaparral shrublands [1]. Chamise was placed at a location 20 cm above the surface fuel in a volume with dimensions 0.3 m x 0.3 m x 0.8 m at a distance of 1.75 m from the front edge the surface fuel. (See Figure 1.) The scale of the laboratory experiments was chosen based on safe practices for indoor experiments, as well as Froude number scaling which matched typical wind speeds and chamise stand heights observed in the natural chaparral habitat [2,6]. Experimental ignition was achieved by the application of alcohol as a propellant, which provided ignition of the surface fuel along the complete width of the fuel bed within 2 seconds. [9].
The crown fuel in the bulk density experiments had three different bulk densities, in order to accurately represent potential chamise crown fuel densities which occur naturally. The gross bulk densities were 1.40, 3.30, and 5.20 kg/m$^3$, with mass proportions of 53% and 47% for foliage and branch fuel, respectively. These proportions result in the various bulk densities reported in Table 2. Surface fire progression was monitored via video camera as it propagated along the length of the fuel bed, and as it encountered the region containing the crown fuel. In the experiments focused on the influence of wind speed on crown fire initiation, three fans were placed 1.75 m upwind of the leading edge of the surface fuel. Three different wind speeds were considered: 0 m/s (Fans off), 1.5 m/s and 1.8 m/s wind fields.

2.2 Modeling Bulk Density Variation

The first set of experiments modeled with WFDS was based on the effect of varying the bulk density of the crown fuel. The original computational domain measured 1.2 m x 1.2 m x 1.2 m, and used a uniform 2 cm grid resolution. The excelsior fuel bed of 10 cm depth was placed on a substrate of K23 fire brick, as was used in the corresponding experimental setup. As shown in Figure 2, the front edge of the excelsior fuel was open, so that there was some flow through the porous surface fuel bed. The area of the surface fuel bed in these cases measured 1.2 m in length and 0.8 m in width. The crown fuel was located at a distance of 0.5 m from the front edge of the surface fuel. The shorter crown fuel preheating length of the fuel bed was used for the sake of conserving computational resources, as well as the operational assumption of a constant ROS given no external influences in the experimental setup. Simulations were run to ensure that this shorter preheating length (i.e., the distance from the start of the ignition location of the surface fuel to the crown fuel) did not affect the outcome. The chamise crown fuel was located at a height of 0.2 m above the surface fuel. (Figure 2). The relevant input parameters for the numerical models are also shown in Table 2.
Table 2. Vegetation input parameters for both sets of simulations. These values were taken from reported values in the laboratory experiments as well as approximate values for vegetation within the WFDS Models.

2.3 Modeling Including the Effect of Wind

The second set of experiments we modeled from the Forest Fire Laboratory included a zero and two nonzero wind speeds. The nonzero winds speeds were nominally 1.5 m/s and 1.8 m/s. The computational domain was extended to match the experimental separation distance between the fans and the excelsior fuel. The domain was extended from the original 1.2 m x 1.2 m x 1.2 m domain to 3.56 m x 1.2 m x 1.2 m, as shown in Figure 3. This included lengthening the preheating zone of the surface fuel bed to a full 1 m as in the experimental setup. For these experiments, the crown fuel maintained the same size and remained fixed with the crown fuel base at 20 cm above the surface fuel. The crown fuel for the simulations including wind is located 2.26 m from the fans’ inlet. Additionally, the single-substrate fire brick under the excelsior fuel bed was changed to match the changes in laboratory conditions. The new substrate had a thin layer of Kaowool fire board placed over the K23 fire brick.

We modeled the original fans from the experiment as a single vent input with a constant velocity boundary condition. While the experimental conditions used three 48 cm square fans to generate the necessary air flow, a single 48.0 cm x 80.0 cm input was used in the numerical model for cold flow.
validations as well as the actual burn simulations.

Figure 3. Numerical domain for WFDS cases involving wind.

Chronologically in the simulation, the wind field was given 15 seconds to fully develop throughout the domain prior to the surface fuel being ignited. Then surface fuel was ignited by the inclusion of a hot element line of grid cells; a section of vegetation embedded in the leading edge of the excelsior whose initial temperature of 1000°C was sufficient to ignite the surface fuel in the 3.5 seconds it remained at that temperature. For this reason, the analysis of ROS and flame parameters were not examined until the igniter extinguished at 18.5 seconds into the simulation, to minimize the effect of the artificially hot element on the collected data. ROS values were measured in the three input velocity cases by visual inspection of the domain centerline in Smokeview, an auxiliary software package used for visualizing the computational results of the WFDS simulations. This allowed tracking of the flame front at the surface of the excelsior fuel bed. Position was recorded at set points along the domain, and provided the ROS data for Figure 6.

3. Results and Discussion

3.1 Experimental Results

The results from the numerical models provide a multitude of possible comparisons to the experimental results. In this case however, only several specific reported values from the laboratory experiments were used for comparison, since not all data from the physical burns was collected in a manner which would make comparisons useful or even possible. We will focus then, on the trends which the model provides, and how they compare to the laboratory experiments. Laboratory experiments measured the ROS of the surface fire using either the time to travel between visual markers or to a single point a measured distance from the ignition zone of the surface fuel. Unfortunately, this leads to inconsistent comparisons with the numerical results since we either don’t know the specific locations/distances at which the ROS measurements were taken, or the measurement was inconvenient for direct comparison with the numerical results. Additionally, crown fuel ignition success was a difficult comparison to make since the laboratory experiments identified successful crown fuel ignition as sustained crown fuel burning after the surface fire spread past the crown fuel. This does not provide a well-defined measure as, for example, of the extent of
crown consumption. Initial and final mass of the crown fuel would provide a useful comparison for the consumption percentage of the crown fuel; we also chose crown consumption as a metric to compare simulations and characterize crown fire initiation.

3.2 Effect of Bulk Density

Visualizing the results of the bulk density simulations in Smokeview, the ROS for the zero wind, but different bulk density simulations was observed to be constant, with a ROS of 1.3 cm/s. This congruency is to be expected, since there was no wind velocity to assist in the surface fire propagation, and the excelsior and fuel bed substrate properties remained constant across all three density cases. At 1.1 cm/s (+/- 0.1), the ROS for the laboratory experiments was slightly slower than the simulated value, but we determined the deviation to be acceptable for our modeling purposes.

<table>
<thead>
<tr>
<th>Foliage Bulk Density</th>
<th>Experimental Observation</th>
<th>Numerical Consumption by Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 kg · m⁻³</td>
<td>No Sustained Crown Fire</td>
<td>Foliage 78 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Branches 3 %</td>
</tr>
<tr>
<td>1.75 kg · m⁻³</td>
<td>No Sustained Crown Fire</td>
<td>Foliage 95 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Branches 52 %</td>
</tr>
<tr>
<td>2.75 kg · m⁻³</td>
<td>Sustained Crown Fire</td>
<td>Foliage 98 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Branches 83 %</td>
</tr>
</tbody>
</table>

Table 3. Experimental and numerical observations for crown fuel ignition in bulk density cases. Consumption increases with density for both sets of investigations.

As shown in Table 3, the experimental bulk density experiments showed a lack of sustained crown fuel for the two lower crown fuel bulk densities, while managing to sustain a crown fire in the chamise at the highest bulk density case. The numerical simulations show a similar trend. While it is difficult to establish numerically what constitutes a sustained crown fire, the numerical consumption data show a very definite increase in crown fuel consumption percentage with increasing bulk density. While there is no direct metric for comparison, the data trends act similarly for both laboratory and numerical results.

3.3 Effect of Wind Speed

Although the modeled wind input was narrower in the cross-stream direction (80 cm) than the original laboratory fan area (144 cm), it still encompassed the width of the surface fuel bed and allowed for a more stable surface fire spread. Test cases modeled with a wider domain (-0.8 m < Y < 0.8 m) and a larger input (48 cm x 144 cm) which matched the dimensions of the fans used in the experiment led to an unsteady surface fire with multiple flame anchors and made it difficult to measure ROS.

Experimentally reported wind profile data was compared to the cold flow profiles generated from this input condition, (Figures 4 and 5). The wind profiles represent the U-velocities along the domain centerline. We have no data for the wind field elsewhere in the experimental domain, so this is the
only comparison we can make. We can see from the data that the experimental wind profiles for both the 1.5 m/s and 1.8 m/s wind cases differ from those determined numerically, most notably at positions in the domain nearest the fan inlet. The experimental values have a much higher initial velocity and rapidly lose velocity upon moving along the length of the surface fuel. In contrast, the inlet boundary condition for the numerical cases maintained a mostly steady flow throughout the length of the domain, with only minor losses in velocity. We decided that this was an acceptable comparison since the wind profiles corresponded very well at a distance of 2.75 m from the inlet face of the fan, which is the location of the upwind face of the crown fuel. (The numerical cases use a 1.76 m distance, since the 2 cm grid resolution prevented the use of distances at odd number intervals.)

Figure 4. Centerline wind profile data for the 1.5 m/s wind cases in both laboratory experiments (top) and WFDS simulations (bottom). A height in the domain of 0.1 m represents the upper limit of the excelsior surface fuel. In the experimental data, the authors set the velocity at \( z = 10 \) cm equal to zero; however, since the bed does allow some flow through it in the computations, the no-slip condition is not imposed and there are non-zero tangential velocities at the surface (\( z = 10 \) cm).
Figure 5. Centerline wind profile data for the 1.8 m/s wind cases in both laboratory experiments (top) and WFDS simulations (bottom). A height in the domain of 0.1 m represents the upper limit of the excelsior surface fuel. In the experimental data, the authors set the velocity at $z = 10$ cm equal to zero; however, since the bed does allow some flow through it in the computations, the no-slip condition is not imposed and there are non-zero tangential velocities at the surface ($z = 10$ cm).
Figure 6. Tracking rate of spread for the 3 cases involving the longer fuel bed and different wind velocities.

Table 4. Spread rate comparison for experimental values and the numerical averages. ROS values were averaged over a 1 m distance from 0.5 m to 1.5 m from the original surface fuel ignition zone.

<table>
<thead>
<tr>
<th>Input Velocity</th>
<th>Experimental ROS (Averaged 0.5-1.5m from Ignition Zone)</th>
<th>Numerical ROS</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m/s</td>
<td>1.9 cm/s (+/- 0.1)</td>
<td>1.7 cm/s</td>
<td>10.5%</td>
</tr>
<tr>
<td>1.5 m/s</td>
<td>3.2 cm/s (+/- 0.3)</td>
<td>3.7 cm/s</td>
<td>15.6%</td>
</tr>
<tr>
<td>1.8 m/s</td>
<td>3.9 cm/s (+/- 0.2)</td>
<td>4.9 cm/s</td>
<td>30.8%</td>
</tr>
</tbody>
</table>

The ROS for the simulations which include wind were measured with the crown fuel included in the model, as was the practice for the laboratory experiments [11]. The position was recorded every 0.2 m after the hot ignition element had extinguished to minimize the potential artificial acceleration effect on the ROS. In all cases, the ROS sees an increase as the fire comes into contact with and ignites the crown fuel (Figure 6). We believe this to be a function of multiple simultaneous effects. In the area of the crown fuel, the wind results in a tunneling effect since the crown fuel acts as an obstruction that the wind must go around, thereby increasing the wind velocity at the surface of the excelsior. Additionally, the burning crown fuel generates buoyancy induced flow leading to an increased wind speed. Lastly, the burning crown fuel provides an additional heat flux on the excelsior potentially leading to an increased ROS. Since these ROS measurements were not reported for this section of the surface fuel bed, we cannot compare these findings with the laboratory experimental results.

The average values for the ROS along the surface fuel are also shown in Table 4. The rate of spread for the zero-wind case is higher than that seen in the previous bulk density cases due to the change in fuel bed substrate. That is, the addition of the Kaowool fire board layer over the K23 fire brick increased the ROS even before the addition of wind. The addition of a wind field to the domain predictably increased the ROS as well. While the averaged numerical ROS values differ by as much
as 31% from the reported experimental values, we still find them to be acceptable for our comparisons. The ROS values increase in a predictable manner which does not deviate from the reported values. Also, as before, the lack of specific measurement criteria in the laboratory papers makes direct comparison difficult, so we find these ROS measurements to be acceptable.

<table>
<thead>
<tr>
<th>Experimental Observation</th>
<th>Numerical Consumption by Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind = 0m/s</td>
<td>Sustained Crown Fire</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind = 1.5 m/s</td>
<td>Sustained Crown Fire</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind = 1.8 m/s</td>
<td>No Sustained Crown Fire</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Consumption trends with wind addition track similarly with increasing wind speed. As in the laboratory experiments, the addition of increasing wind speeds decreases the consumption of the vegetation in the crown fuel area.

The results of the laboratory experiments show sustained crown fire ignition for both the zero-wind experiment, as well as the low-wind case. The high wind case, however, shows a lack of crown fire ignition. These results as well as the numerical simulation results are reported in Table 5. As with the bulk density consumption results, we see a trend in the numerical results that accurately matches the experimental observations. The simulations with either no wind or low wind velocity saw a greater consumption by mass of the crown fuel than was observed in the high wind case. It is worth noting that if we increased the wind speed to 2.1 m/s (an increase of 0.3 m/s, or 17%), crown consumption dropped significantly to 12% for foliage and 0% for branches.

4. Conclusions

The correlation between the results of the laboratory experiments and the numerical simulations were good across both examination campaigns. The increased bulk density decreased the ignition success of the crown fuel in both experimental and numerical results. One difficulty in this area is the packing density of the crown fuel. The uniform packing densities of the chamise foliage and roundwood in the simulation model are unrepresentative of naturally occurring density distribution of chamise stands, or of the packing density in the laboratory experiments. Despite its importance as a mechanism of heat exchange and ignition within the crown fuel, mapping hot gas velocity within the crown fuel region becomes an inconclusive comparison metric. Future studies which more closely map the density and particle distribution of chamise stands into the numerical model could provide a much better comparison. However, despite the uniform packing density assumptions made with the crown fuel in these experiments, the trends which were observed fall consistently in line with the experimentally reported results.
The hydrodynamic validation of the wind models within this small scale experiment had very little experimental data to use for comparison. The domain centerline data which was used was minimal. The inclusion of a narrower fan for the numerical cases resulted in a surface fire which was easily tracked, but we cannot know the effects of the wind field variations in the width of the domain since we don’t have data on the wind field there. Knowing the wind effects at the domain boundaries and at other points in the domain would allow us to better understand why the wind speeds decrease throughout the domain in the experimental cases, while they are maintained throughout the numerical simulation domains. This deficit notwithstanding, the wind fields imposed in the numerical domain gave ROS values which suitably matched the experimental ROS values for the wind, substrate, and surface fuel conditions used. These values all added to a final result of similar crown ignition for both experimental and numerical cases. The increasing wind velocities contributed to a consumption of the crown vegetation.

Overall, this examination validated the efficacy of the WFDS models in predicting crown fire ignition from a surface fire when compared to the experimental data available. Future work in this area in both experimental and numerical case studies could provide significantly more data for comparison and a much more comprehensive validation of the existing WFSD models.

Acknowledgements

This research was funded by the National Institutes of Standards and Technology (NIST) Cooperative Agreement 70NANB12H165.

The authors would like to thank Dr. Alex Maranghides at NIST for his assistance, Tachajapong, et. al. for their cooperation in providing details regarding their experiments not available in the article texts, as well as colleagues in the SDSU Combustion and Solar Energy Laboratory for discussions about WFDS and computational modeling in general.

References


[8] Rothermel, R.C. 1983. *How to Predict the Spread and intensity of Forest and Range Fires* Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

