Forest Fire Modeling

Fire Dynamics Simulator to model the burning of Sugi logs

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Fire has long been a source of wonder, amazement, and fear. Since prehistory, the workings of fire have baffled people. How is it created, how does it spread, how can one best protect oneself against its dangers? As science has allowed for a better understanding of fires and has begun to answer these questions, more complex questions have emerged. These questions are extremely prevalent when studying wildfires. Increases in development near wildlands and extended droughts have contributed to hundreds of severe fires and large property losses since the 1980s (Cottrell iv). In the country of Japan, large scale forest fires account for only 0.24 percent of all fires, yet they consume 47.4 percent of the total area damaged by fire (Inoue "Estimation of Wind Velocity" 2). A greater understanding of wildfires is needed as an aid to prediction and control of these fires.

Research is currently being done to study and analyze the mechanism of forest fire propagation so that prediction of possible spread of fire can be improved. This work should allow for more effective fire fighting as well as for better control of prescribed fires. Fire propagation depends on an array of complicated factors including the condition of the forest floor fuels, topographical features, wind direction, wind velocity, and other weather factors (Inoue "Estimation of Wind Velocity" 2). Fire in simplest terms is a chemical reaction that combines fuel and oxygen to produce heat and light; however, this definition of fire does not begin to account for the exceptional properties that fire possesses. Wildfires are unique in that they involve a changing situation. Fire itself changes its own environment because of the winds it creates (Hall). This ever changing environment as well as the high temperatures created during the life of a wildfire makes close, direct observation of fires dangerous and costly. Currently, there are no observational tools available that are able to withstand the 800°C or higher temperature of the air in wildfires or able to withstand direct contact with flame. Because of these limitations, researchers have begun to use wildfire modeling tools to understand and predict wildfire behavior.

Fire Dynamics Simulator (FDS) and Smokeview Introduction

Scientists have begun to use computational science to design numerical simulations of wildland fires. Complex physical models that allow for simulations in three dimensional models have recently been developed. One modeling tool that has been widely used is the Fire Dynamics Simulator (FDS). FDS is a computational fluid dynamics model of fire-driven fluid flow. The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires (McGratten et al. 24).

FDS was originally created to model residential and industrial fire reconstructions and to model the behavior of smoke for smoke handling systems and sprinkler/detector activation studies. The simulator is meant to be a tool to study fundamental fire dynamics and combustion. FDS and information on FDS is hosted at the National Institute of Standards and Technology (NIST). FDS was released to the public in 2000 and is currently in its fifth version.

A new adaptation of the FDS model is the Wildland Urban Interface (WUI) Fire Dynamics Simulator (WFDS). This new extension of FDS has created the capability for wildfire simulations. WFDS includes vegetation as a possible fuel. This new extension also uses computational fluid dynamics methods and does this in order to solve the governing equations for buoyant flow, heat transfer, combustion, and the thermal degradation of vegetative fuels (Mell et al 7). The development and validation of WFDS is part of NIST's wildland-urban interface project. FDS5 has all of the capabilities of WFDS added to it and WFDS can now be run through FDS5. However, FDS5 does not yet advertise the WFDS capability and the user manual for the fifth version does not mention this capability. Information about WFDS is available exclusively online while early validation of WFDS models continue.

FDS requires a separate visualization program in order for the results to be displayed. Smokeview is an advanced scientific software tool designed to visualize numerical predications generated by fire modes such as FDS (Forney 3). Smokeview allows the researcher to visualize the fire attributes realistically by displaying a series of partially transparent planes where the transparencies in each plane are determined from soot densities computed by FDS (Forney i). It visualizes smoke and other characteristics of fire such as temperature through a real time simulation. Visualization of smoke and other characteristics is done through displaying tracer particle flow, 2D or 3D shaded contours of gas flow data, and flow vectors showing flow direction and magnitude (Forney i). It is also possible to obtain static data for a specific time.

FDS, WFDS, and Smokeview are all free software developed through NIST in cooperation with VTT Technical Research Centre of Finland.

Fire Scarring as a Measurement of Wind Velocity and Vortices

In order for effective fire fighting and prevention, the propagation of fire must be understood. There are a number of factors that are important to fire propagation: conditions of forest floor fuels, topographical features, wind direction, wind velocity, and other weather factors. While many of these factors can be measured from past data or through satellite and weather information, no good way to measure wind direction and wind velocity during a fire has been found. Often data on these factors is gathered from weather stations a few kilometers from the fire site or through data based on AMEDAS (Automated Meteorology Data Acquisition System). This makes the accuracy of this data less reliable (Inoue “Field Experiments” 16). There is also no means available to obtain data on the direction and velocity of whirlwinds created within the fire. Fire-scar remaining on the trees at the site of forest fires is thought to be one parameter that can be used to indicate the wind direction and velocity when trees are burnt (Inoue “Estimation of Wind Velocity” 3).

To understand this complex phenomenon, definitions used to describe different aspects of fire need to be understood. A fire scar is the wound or mark left on the bark of the tree trunk and is caused by contact with the fire. The tree’s cambium is the layer of living cells found in between the bark and the hard wood. Cambium produces new bark and wood cells and is the part of the tree responsible for new growth. If a large portion of the cambium is damaged by fire, the tree will die. The forest floor is composed of three main parts, litter, duff, and mineral soil. The litter found on the forest floor, also called the top layer, affects the spread rate of fire and will thus affect the fire scarring. Litter is made up of debris from the vegetation that has not yet begun decomposing. Duff is the layer under the litter and is composed of decomposing materials such as twigs, needles, and leaves and mineral soil is the layer of soil directly under the duff. Mineral soil has little combustible material in it. The leeward side of a tree is the side of the tree that is opposite the wind direction, it is defined relative to the wind direction. The fire scar on the leeward side of the tree will be taller than the fire scar on the windward side of the tree. A head fire is a fire that is spreading or set to spread with the wind (NWCG Glossary) and is sometimes called an advancing fire. A backing fire is a fire spreading or ignited to spread against the wind or a fire that is burning downslope. If a fire is spreading and no wind is present, it is also classified as a backing fire (NWCG Glossary). A backing fire normally has a slower rate of spread and is of lower intensity than a heading fire. One of the more complex aspects of fire is the whirlwinds of fire that are created. Fires generate convective updrafts (Cottrell 51). If this updraft is given a spin, a whirlwind develops. These fire whirls increase burn rates and deplete fuel quickly (Cottrell 51). Whirlwinds develop during very intense fires and, while generally small, tornado-like whirlwinds may be produced in very large fires.

Fire scarring is caused by fire and is the injury left on woody vegetation. Fire scar analysis is an analysis of fire scars to determine individual tree fire frequency or mean fire intervals for specified areas (NWCG glossary). This analysis has been expanded recently so that the scars can also be used to calculate other data to help understand fire propagation. There are four key observations associated with the formation of fire scars (Gutsell and Johnson 166). The first is that when a fire passes by a tree, the fire increases in height on the leeward side of the tree. This observation is true for both heading and backing fires and is a result of the occurrence of two leeward vortices. The height of the flame increases in the vortices because the turbulent mixing of fuel and air is suppressed (Gutsell and Johnson 167). Combustion can occur as the flow of fuel in the vortices becomes greater than the rate of mixing with the air. Another observation is that fire scars are found only on the leeward side of trees. This is due to the vortices increasing the residence time of the flame on that side of the tree. The flame spends far less time on the windward side of the tree, causing differential heating around the base of the tree. The additional time the tree stem on the leeward side spends in direct contact with the fire causes a higher amount of scarring to occur on that side when compared to the windward side. In addition, the diameters of trees also greatly affect the height of the fire scar and a side result of this is that small trees rarely have fire scars. The smaller trees cambium is completely killed off by the passing fire (Gutsell and Johnson 166), the bark char is too great to measure and tree recovery will not happen or their foliage is killed by crown scorch. The fourth property of fire scars are that they are triangular in shape, with the base as the widest portion and becoming narrower with height. This triangular shape is a result of the triangular shaped temperature isotherms (Gutsell and Johnson 167) within the standing leeward flame.

These four observations have all been studied and the properties of fire scarring are currently being used to help predict or explain wind direction and velocity. The vortices that are created around trees greatly effect the scarring found on trees and are a perfect parameter to begin measuring so that estimations of hard to observe variables, such as wind direction and velocity, can be studied. Studying scarring on trees is specifically being applied to estimating the properties of whirlwinds created within the fire.

Shoji Inoue's Estimation of Wind Velocity from Stem-Bark Char

Methods of the Experiment

Fire scarring is seen as a vital parameter in measuring wind direction and velocity, but prior to 1999, no quantitative analysis had been made on how the whirlwind direction and velocity are related to fire behavior (Inoue "Estimation of Wind Velocity" 2). In Shoji Inoue's paper, "A Fundamental Study on Fire-Scar of Stem in a Forest Fire- Estimation of Wind Velocity from Stem- Bark Char by Examination using Wind Tunnel" Inoue develops a method to estimate the wind direction and velocity at the forest fire and thus clarifies the relationship between factors affecting fire scar of a stem. Inoue presents the results he obtained by running fundamental burning experiments using a wind tunnel.

Inoue used a wind tunnel with dimensions of 42cm by 42cm by 200cm. The sides of the wind tunnel were constructed out of entirely heat and fire resistant material with one side of the tunnel constructed out of heat resistant glass so that visual observation could occur during the experiments. In order to measure the distribution of wind velocity within the tunnel, Inoue placed 20 observation points at four sites of different heights throughout the tunnel. The results from these 80 points showed almost constant velocities, with only minor fluctuations. Constant velocities were important in showing the construction of the wind tunnel did not interfere with the distribution of the wind velocity and allowed the researches to continue with the experiment.

The experiment was done in Japan, so Sugi (Cryptomeria japonica) logs were chosen for the type of tree in the experiment. Sugi trees are one of the most commonly found trees in forests and Sugi trees also show fire scarring well. All logs were cut to a height of 30cm so that there was still area above the log in the wind tunnel. Inoue and his team used oven dried recycled paper to represent the litter on the forest floor. The paper was cut to 3mm by 5cm and was spread in a fixed volume over the area of 40cm by 100cm, with the paper in the center of the wind tunnel. Paper was chosen as the litter because of the stable conditions it shows during burning.

Stem bark char and scarring are affected by the diameter of the log as well as wind direction and velocity. The experiment was conducted to study the relationship among these factors. Because of this, the diameter of the stems and the wind velocity were carefully recorded. Stems with 4cm, 6cm, and 8cm diameters were used; diameters of this size still allow for adequate wind flow around the stem considering the constraints of the wind tunnel. Wind velocities of 1.0, 2.5 and 4.0 m/s were chosen, at these levels, burning material did not yet begin to scatter. A picture of the layout of the experiment is shown below in Figure 1, the size of the log is not drawn to scale.

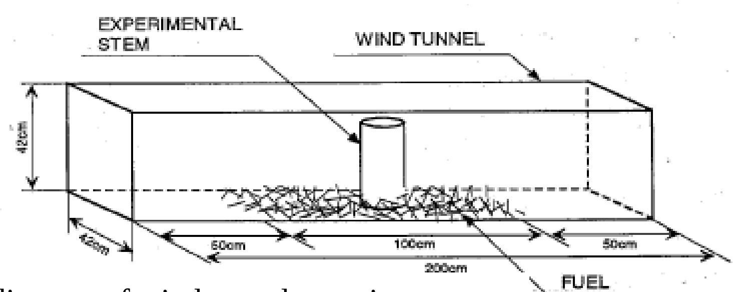


Fig. 1 Schematic diagram of wind tunnel experiment
Inoue "Estimation of Wind Velocity" 4

Two forms of ignition were used in the experiment, one in which the fire was progressing windward and one in which the fire was progressing leeward, in this manner, both heading and backing fires were studied. Thirty-six burning experiments were run using these two forms of ignition with different combination of wind velocity and stem diameters. Six experiments were run to study that impact of the forest floor on the height of fire scar stems; two parameters of stem diameter and wind velocity were used.

Results of the Experiment

Inoue found that the height of the fire scar was larger on the leeward side of the stem than the fire scar found on the windward side of the tree. This result is true for both heading and backing fires, showing that the height of the fire scar is decided by wind direction, not by the direction the fire is progressing. From these results, researches and investigators can determine the wind direction at the time of the fire based on the burn marks on trees by studying the height of the fire scars on the trees.

Figure 2 below is a sketch of what Inoue and his researchers found. H1 will be used to describe the height of the fire scar on the leeward side of the tree and H2 will be used to describe the height of the fire scar on the windward side of the tree. The stem on the left exhibits both continuous charring and scattered charring above. The continuous charring is thought to be produced by exposure to flame over an extended period of time. Continuous charring can be used as a general indicator because it is unaffected by the property of each stem. Scattered charring is caused by the height of the flame but is not useful as an indicator for studying velocity because the conditions of the bark affect this result so highly.

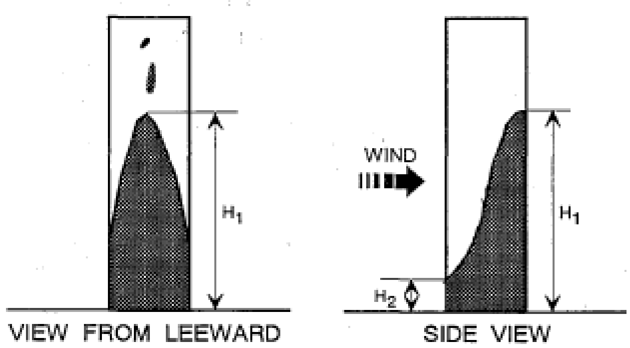


Fig.2 Sketch of fire-scar of stem after burn

H_1: height of fire-scar registrated at the leeward face of stem
H_2: height of fire-scar registrated at the windward face of stem

Inoue "Estimation of Wind Velocity" 5

The height of the fire scar on the leeward side of the tree, H1, showed interesting results. The fire scar height increased as the diameter of the tree increased, but changed little as the wind velocity changed. This is true for both heading and backing fires. As the diameter of the tree increased, more area was protected from wind and the flame was able to grow higher. These results show that H1 can be a factor to indicate the influence of the diameter of the stem but that it cannot be used to study the magnitude of wind velocity. H1 was found to be higher in the case of a heading fire with an increased wind velocity, but if wind velocity was below 1.0m/s no difference was found. H2 on the other hand showed almost no change based on the diameter of the tree and showed little difference based on heading or backing fired. H2 can be used as a direct factor to indicate the influence of wind velocity.

From these results, Inoue measured a new variable, Hd=H1-H2. Hd is an important factor to indicate the change of wind velocity and the diameter of the stem (Inoue "Estimation of Wind Velocity" 7). It is larger in a heading fire than a backing fire; a heading fire creates a large flame but in backing fires the stem is burned twice by a small flame, making Hd smaller. The relationship found between the quantity of fuel on the ground, litter, and the height of the fire scar is also note worthy. The researchers found that Hd does not change based on the amount of fuel on the forest floor. Hd maintains its fixed value because both H1 and H2 increase as the amount of fuel increase and since Hd is the difference of these two measurements, no change is found. This result is important because it shows Hd can be used as an indicator of wind velocity and stem diameter even when litter cannot be measured.

Conclusions drawn on the importance of Hd are all from the wind tunnel experiment, so Inoue first investigated any problems that may have arisen due to the scale of the experiment. Due to the height of the wind tunnel, the stems of the tree were restricted to 30cm in height. The height of the stem limits the maximum height of Hd to 30cm also. However, research found an Hd of 30cm would only account for 10 percent of cases in Japanese forest fires. Due to this limitation, Inoue and his team began to look at the ratio of H1/H2 instead of the difference between H1 and H2. This ratio was named Hr and is regarded as a common, but relative, factor (Inoue "Estimation of Wind Velocity" 8). Since it is a relative factor, Hr cannot estimate wind velocity solely and must be combined with Hd. Using this new information, Inoue created the variable H=Hd*Hr which he combined with the difference in heights as [H1-H2]*H. This value was determined to be an accurate predictor of wind velocity at the fire site.

Verification of Inoue's Equations for Wind Velocity using Field Experiments

Inoue's equations were created solely based on his observations from the wind tunnel experiment. In order to verify the equations for the estimation of wind velocity, it became necessary to measure the wind velocity found around burning trees in a real forest fire. Verification was complicated by the fact that no anemometer is able to withstand the heat found in forest fires. Because of this, a special experiment was conducted.

The researchers decided to use prescribed fire at Akiyoshidai, Yamaguchi Pref and also at Hiraodai, Fukuoka Pref for validating their results. The prescribed fires at these two sites had conditions similar to real forest fires. On the slope of each site, 38 Sugi logs were set. Sugi logs were used to replace the Sugi stems from the wind tunnel experiment. The velocity and direction of the prevailing wind were measured at selected points at both sites. Videotapes were also recorded at both fire sites so that survey maps of the fire could be created. These tapes were used to measure the scene of the burning, the time of the burning of each log, and the fire progressing direction.

There were differences between the observed values from the field experiment and what the equations would predict, but these differences were small and the equations were found to be adequate tools to use when measuring wind velocity in forest fires. Four of the logs found in Akiyoshidai showed the fire scar caused by the prevailing wind rather than by any whirlwinds. This was explained by the fact that when fire is in its initial stages or as fire weakens its heat is not high enough to create whirlwinds. The four logs found with fire scar caused by prevailing wind were either at the beginning or edge of the fire. Prevailing wind velocity during the fire was measured by anemometer that was a distance of 100m to 200m away from the experimental logs and other unstable conditions in the field experiment. This distance between the log and the anemometer help explain some differences found in the field experiment. On average, the observed values and the calculated values were found to be similar. There were a few cases where there were differences in the observed value and the calculated value, but the differences were small enough to be explained by the distance between the log and anemometer. The consistent results verify the applicability of the equation for the estimation of wind velocity.

Modeling Inoue's Results using WFDS and Smokeview

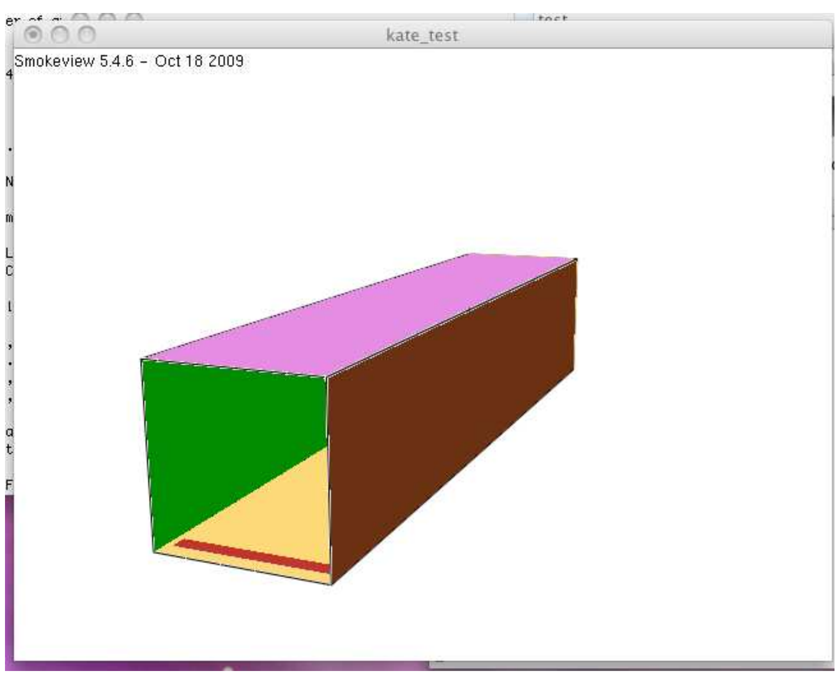
The estimated equation for measuring wind velocity has important implications in wild fire research. This new equation allows researchers to better study wild fires, as well as for estimations of wind velocity to be made for wild fires as well as for prescribed fires. Since the propagation of fire is difficult to predict and to measure, being able to predict this propagation is extremely important. Inoue's experiment shows how complex measuring fire can be as well as how difficult taking small measurements can be. While experiments like Inoue's are vital to bettering the understanding of fires, they are expensive, capital heavy, and take time to complete. A more efficient and effective way of modeling wildfires can now be done using computational fluid dynamics through computer modeling.

As discussed earlier, WFDS is a computer modeling tool used in studying the dynamics of fire. Since WFDS is a newer tool, replicating Inoue's experiment through WFDS will help to show the usefulness of this tool in wild fire simulations as well as act as another way of validating the equation used in measuring wind velocity.

The first step we took in modeling Inoue's experiment was to create an input file that would have the basic properties needed to set up his experiment. The FDS manual suggests when looking at a new scenario to first select a prewritten input file and then make necessary changes. The input file used to model Inoue's experiment is loosely based off of an input file originally created by Dr. Matthew Dickinson, a research ecologist for the US Forest Service. The file created by Dickinson was used to model a similar experiment to Inoue's that was done in the United States. For this model, Dickinson's file served as a base but his file has been significantly changed and altered to meet the conditions of Inoue's experiment. The input file we created to replicate Inoue's experiment was named input_Sugifirescar.

Figure 3 is a screen shoot from Smokeview of the initial set up of our model. In this screen shot, all boundaries for the outside walls are shown and the red rectangle on the floor of the wind tunnel shows the vent for the fire. Objects in Smokeview can be rotated so that the scene can be viewed through multiple angles. In this picture, the wind tunnel was rotated so the vent could be seen.

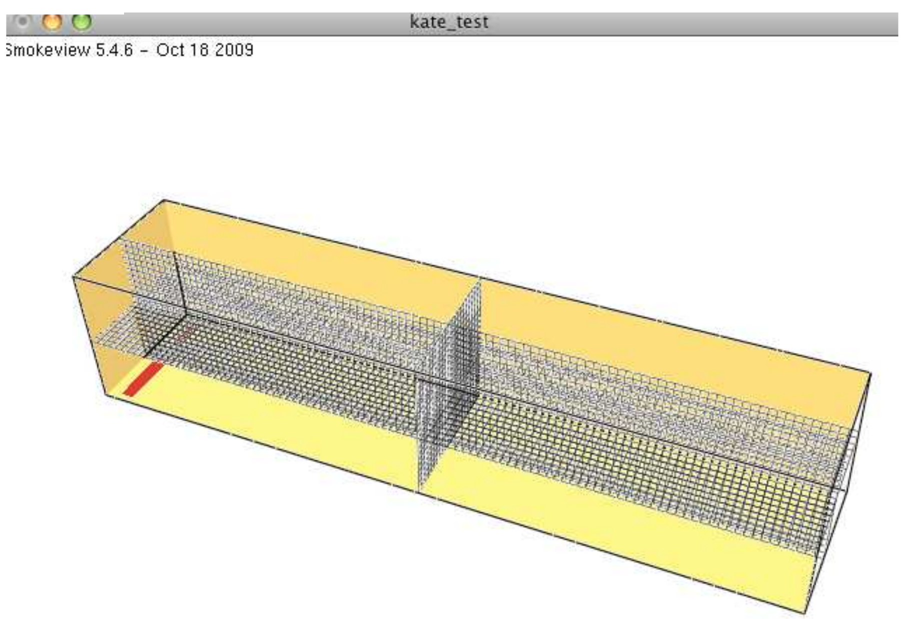
Figure 3 initial set



WFDS allows boundary conditions to be specified and material characteristics can be given to these boundaries. In Inoue's paper, he states that entirely heat and fire resistant materials were used for the walls and floor of the wind tunnel but gave no further specification. Due to this lack of detail on the material used, the input file we created for this model uses the material characteristic of inert. 'INERT' is the default condition and provides a non-reacting solid boundary whose temperature does not change (McGratten et al. 65). This classification was given for both the material and surface identification of all walls in our model. Later versions of the input file will need to change the identification for one of the walls so that it represents the properties of heat resistant glass.

WFDS allows for each individual user to specify the number of grid cells in an experiment. Currently, the grid size for our model is set to 2cm grid cells. This is a rather large grid cell size for the measurements trying to be captured, but it allows for quicker run times as the input file is being constructed and checked. Once the basic features are verified the grid cell size will be lowered to 1 cm grid cells or 0.5 cm grid cells in order to give a better representation of what is taking place in the model. A uniform mesh is ideal and is used in our model. Grids can also be placed in Smokeview to help analyze data and to help verify that the input file was set up correctly. Figure 4 below shows our wind tunnel with x,y,z grid shown. This grid allows for the model to be checked and to make sure that boundaries and other obstructions are placed in the correct areas of Smokeview. In this example, we were checking to make sure the vent had been placed correctly.

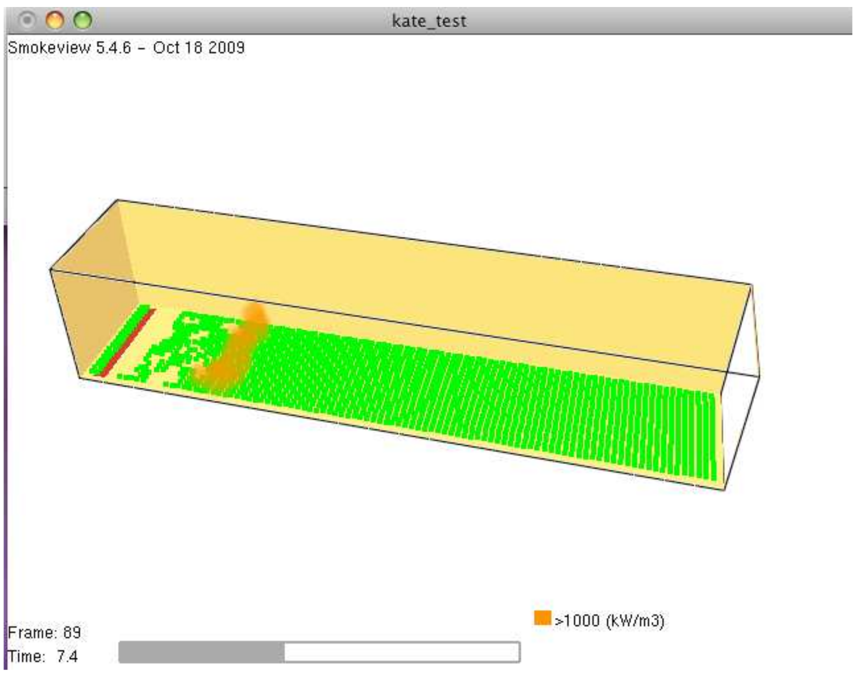
Figure 4 x,y,z Grid



In WFDS a 'VENT' is a used as a means of applying a particular boundary condition to a rectangular patch on a solid surface (McGratten et al. 49). For input_Sugifirescar, fire was originally created using a vent. The solid obstruction of the tunnel floor was used to place the vent on and the area of the vent was given a new surface identity, 'IGN FIRE'. This identity overrides the floors surface identity and allows the vent to be used to create fire based on our input specifications. This vent was made to almost span the bottom face of the tunnel in the y direction but we left 2 cm on each side so that the vent did not touch the outside wall boundaries. It was made 4 cm wide in the x direction. A long vent was used so that a uniform fire front would cross the wind tunnel.

Figure 5 shows the vent, the red rectangle, with the created fire. In this picture, the fire has caught and is now spreading across the grass. Smokeview is showing the flame progress during the simulation. Smokeview gives the researcher the option of showing the flame as it progresses, showing smoke as it progresses, or showing both. This screen shot also takes advantage of making the barriers of Smokeview an outline so that we can see what is happening inside the wind tunnel during the simulation.

Figure 5 Fire Spread Across Grass



The vent was placed in the front of the wind tunnel to create a heading fire. When the vent was at the front of the wind tunnel, changing the wind velocity affected the rate of spread, but the fire was always able to catch and burn. In the case of a backing fire, when the vent was placed at the back of the wind tunnel, wind velocity had to be kept extremely small in order for the fire to catch. Changing the fire from needing to catch the litter of the floor to a radial fire spread will hopefully help with this problem for future changes in the input file. Creating a radially-spreading fire will require some revision of the vent, but a radially-spreading fire will allow the fire to spread at a specified rate created through the vent. When this is done, the spreading of the fire based upon litter is no longer important, but it becomes more difficult to make sure the fire will be a uniform front when it reaches the tree.

The figures below are examples of radially spreading fire seen by using a boundary slice file. Figure 6 is a radial fire just beginning.

Figure 6 Radial Fire Spread Initial

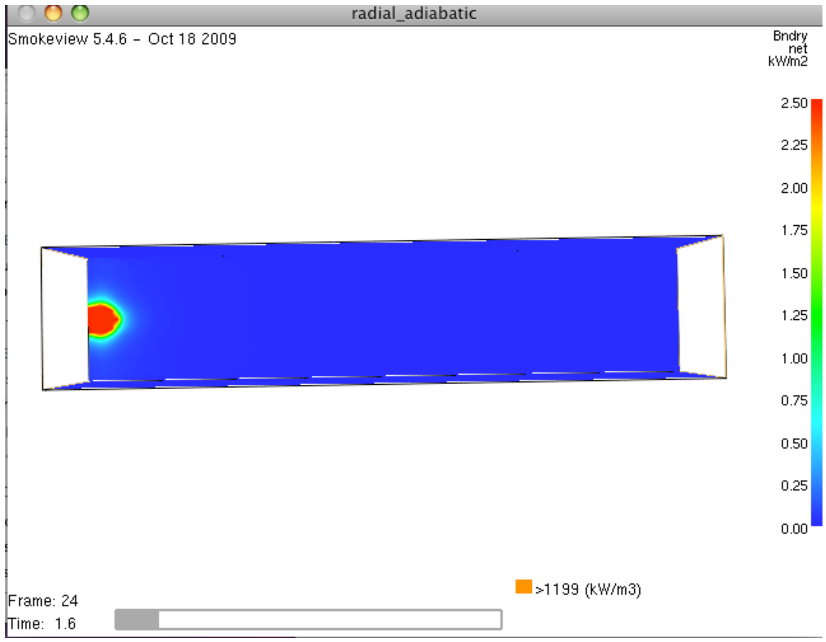
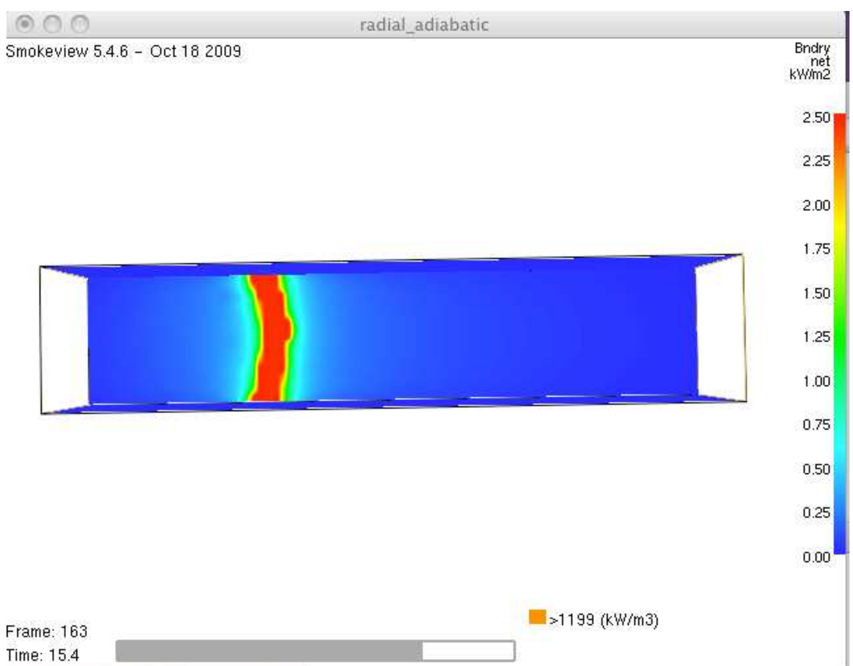


Figure 7 is a radially spreading fire at time 15.4 seconds. The fire is widening and will be a uniform fire front when it hits the middle of the wind tunnel. This is important because in future models, the stem of the Sugi tree will be placed here and a uniform front is needed to accurately measure the fire scar.

Figure 7 Radial Fire Uniform Front



Two other types of vents were also used in our model. The far small face of the wind tunnel was created so that the entire face was an open vent, and the front small face was created so that the entire face was an inflow vent. By specifying the vents in this manner, air is pulled through the wind tunnel. The benefit of pulling air through the wind tunnel rather than pushing it through, like the use of a fan would do, is that turbulence in the air is greatly reduced.

Because WFDS only allows rectangular constructions, creating a tree stem is difficult. Using a matlab file to create the cylinder in FDS was suggested by Anthony Bova, a physical scientist at the USDA Forest Service. Bova supplied his code for use in input_Sugifirescar. This was recently incorporated into the input file and has not yet been run. The file creates many small blocks and stacks them on top of each in a cylinder shape. The cylinder will not be smooth since it is created out of many blocks, but the lack of smoothness is representative of many types of bark and will not be significant in the burning of the tree. Through the input file, the model should create a fire spreading at a constant rate that reaches the tree stem in the middle of the tunnel, and the tree stem should experience fire scarring. Once this is successfully created, parameters within the input file will be changed to meet the different experimental conditions Inoue constructed in his wind tunnel experiment.

Smokeview also has the ability to create 2D and 3D slice files. Slice files can look at simulation qualities such as temperature, gas velocity, and heat release rate. The radially spreading fire figures above are one example of these slice files, in the above case a boundary slice file. Specific temperature vector slices were written into input_Sugifirescar. These vector slices have the model record temperature data at each time step. The temperature vector slices help show how heat is increasing, the affect wind velocity is having on temperature and flames, how intense certain flames become, when the fire dies in certain areas of the model, and when the tree catches fire. Figure 8 below is a screen shot of a temperature slice file. The fire in this figure is not an overly intense fire and temperatures remain relatively low. In this example, the fire was burning only grass.

Figure 8 Temperature Slice File

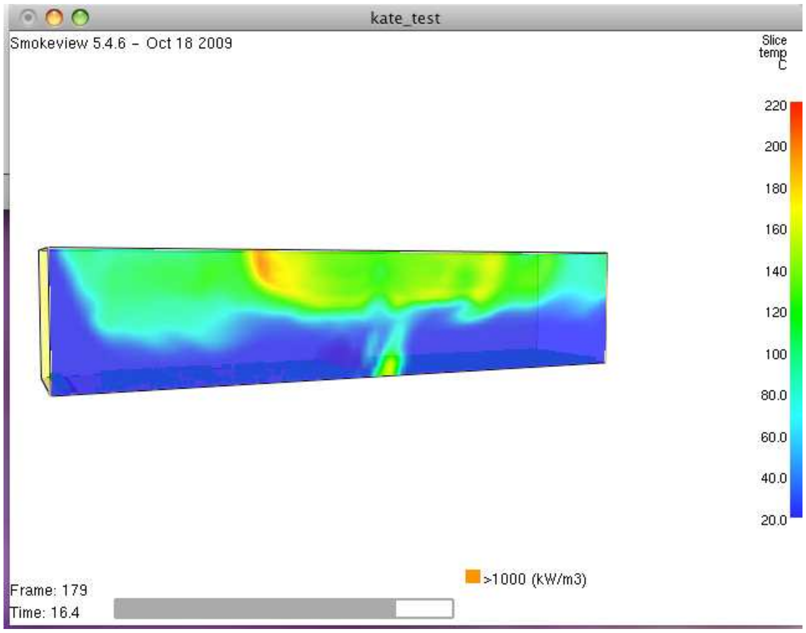
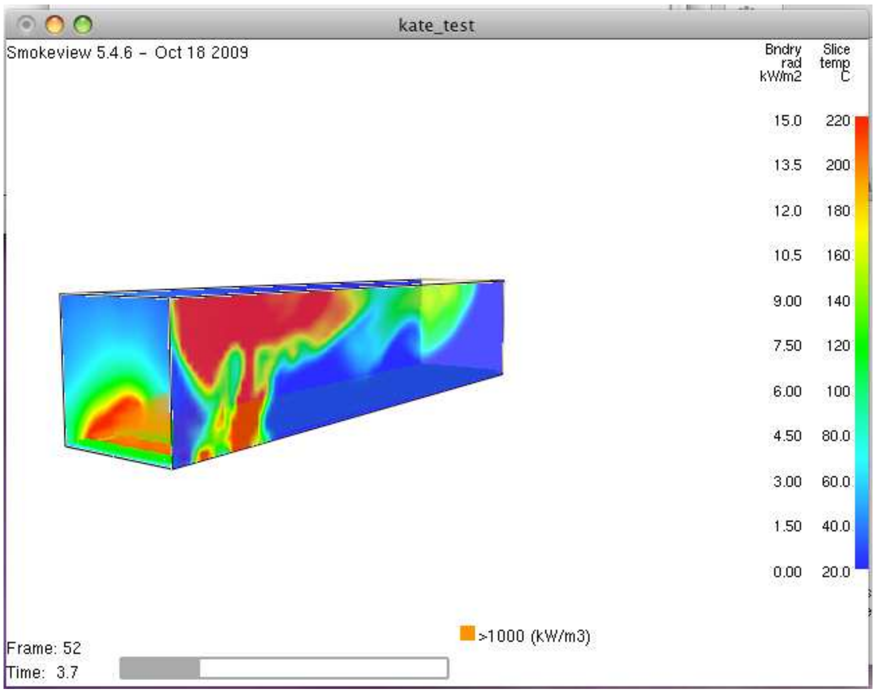


Figure 9 below is an example of both a temperature slice file and boundary slice file measuring radiative heat flux. This figure shows a more intense fire reaching top temperatures. This fire is early in the simulation and the screen shot captures the ramping of the vent. It also shows how the top boundary, the ceiling, is interacting with the heat. This interaction will need to be considered in further tests.

Figure 9 Temperature and Boundary Slice File



The purpose of constructing this model is to try and replicate the results found in Inoue's experiment. If this is successfully completed, two different purposes will be served. It will provide an additional validation to the math equations Inoue wrote to measure wind velocity. Inoue's equations have been used in at least three different field experiments and have been found to be accurate, but mathematically modeling his results will add an additional level of validness to his equations. Since WFDS is a new extension of FDS, validating the results of Inoue's experiment will also show that WFDS is an accurate tool to use in wildfire analysis and can be applied to this expanding study.

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