Modelling of wildland fire spread using empirical approach analysing the effect of moisture, wind, and slope

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Abstract. Due to rapid climate change, wildfires are an increasing risk to human life and economy. To prevent their occurrence and reduce their intensity, computational methods have been developed to study and simulate wildfire spread. Medium scale experiments and thermogravimetric analysis is conducted for Pinus Sylvestris Needle. Results from numerical analysis using level set model were validated using experimental data. And a parametric study was performed to study the effect of fuel moisture fraction, wind and slope to surface vegetation fire behaviour. Numerical data, including temperature and rate of spread, are analysed and limitations of model is also discussed.

1. Introduction

Due to climate change, during the last few decades there has been an increase in the frequency of wildfires worldwide, leading to life losses, environmental and economic cost [1]. Hence, it is of great importance to look for an effective method to stop this trend from continuing.

Surface fire, as a category of wildfire, refers to the combustion of dead or dry vegetation that is lying or growing just above the ground. Intensity and scale of surface fire largely vary as it is depending on multiple factors. The three major factors are commonly believed to be terrain (slope), fuels and weather conditions [2]. Wind, as experiments indicated, has the greatest influence to flame spread in wildfire [3]. In Rothermel's model [4] fire speed is positively related to wind speed for fuel of 0.5 kg/m^2 dry mass 10 cm deep with surface area to volume ratio of 80 cm^{-1} at various moisture level. This correlation was also proved by wind tunnel tests of a flame propagating down a single line of 4.175 cm high Australian match splints as a function of tunnel speed conducted by National Bushfire Research Unit [5]. Burning of fuel on a slope can form a plume, radiant heat from which will help to ignite unburnt elements on the top, hence speed of flame spread is increased [6]. Silvani et al. [7] performed nine experiments at three slop angles, 0^o, 20^o and 30^o with a controlled fuel sample. Results of rate of spread (ROS), generated from experiments, ranged from 0.013 m/s (at 0^o) to 0.093 m/s (at 30^o). Grasses and shrubs are the predominant fuel for surface fire [8]. Generally, vegetation goes through similar pyrolysis process when exposed to heat, starting with dehydration, and followed by decomposition of wood components, including cellulose, hemicellulose, and lignin. As vegetation of various species has different moisture content and different composition of each wood component, its fire behaviour can vary dramatically [9].

Computational Fluid Dynamics (CFD) method have been a common tool of research due to its financial cost saving. Fire Dynamics Simulator (FDS) is one of CFD tools developed by NIST [10] and its source code is open. FDS employs large-eddy simulation (LES) to calculate flows and is able to simulate combustions, smoke and heat transport from fires in various weather conditions [10]. WFDS refers to WUI (wildland urban interface) fire simulation in FDS [10]. Leventon et al. [11] investigated decomposition models for six different wood species, leaves and stems tested separately. All thermal properties, including the onset temperature of decomposition, the temperature range of decomposition, the number of apparent reactions, and the peak measured mass loss and heat release rates, were coded into FDS and tested in a wildfire model. Valero et al. [12] studied the effect of moisture fraction of fuel, fuel depth, fuel load, fuel particle size and wind condition to uncertainty range of ROS. The model was validated by results from CRISO grassland F19 experiment. Other researchers have also emphasised on heterogenous patterns of vegetation. Lagrangian particle model and boundary fuel model were combined in FDS to simulate fuel distribution in High-density cork oak forest stand [13]. By analysing temporal heat flux and heat release rate readings under two different background conditions, together with snapshots as rendered by Smokeview, it can be visualised how distribution pattern of trees in the cleared area affects the wind patterns nearby the dwelling. Wang et al. [14] investigated the wildfire spread in inclined trenches using solid-gas two phase model in FDS. Vegetation was simulated by Lagrangian particles as a homogeneous fuel bed lying on an inert bench in FDS, property input generated from Thermogravimetric Analysis (TGA). Bova et al. [15] compared simulation results using a level set Eulerian approach (as implemented in WFDS) and a marker method (as implemented in FARSITE) at various topographical complexity. Estimation of fire spread in two models mostly matches with each other with minor deviation at complex terrain.

To the author's knowledge, there is limited research on validation of level set model against experiment results. This study aims to investigate the accuracy of this simulation tool under no slope no wind and 30^o slope no wind conditions. A further parametric study is then performed to investigate the effect of moisture content and wind input on flame spread. Numerical data, including temperature and rate of spread, are analysed and limitations of model is also discussed.

2. Methodology

Medium scale experiments are carried out with Pinus Sylvestris Needle as fuel [16]. Needle sample of 0.035m fuel depth and 0.3 kg/m^2 fuel load is placed on a $0.6m \times 0.2m \times 0.2m$ tray, Figure 1. Six type K thermocouples 1.5 mm diameter are used; 3 located at the bottom (TC1, TC2 and TC3) and 3 at 0.03m above the needle bed (TC4, TC5 and TC6). Experiments were conducted under no wind conditions at 0^o and 30^o slope. Rate of fire spread (ROS) is recorded.

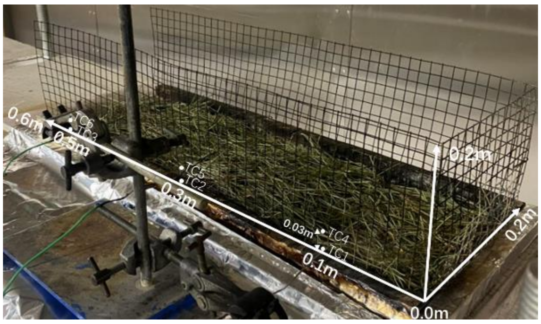

Figure 1 Medium scale experiment setup.

To generate the fuel properties and understand pyrolysis mechanism, thermogravimetric Analysis (TGA, TGA 1 STAR^e System) is used. Pinus Sylvestris Needle sample is grinded into powder and heated in TGA test under Nitrogen gas flow. In the first stage, temperature rises from 20^{o}C to 100^{o}C at 20 ^{o}C /min heating rate. In the second stage, temperature within TGA chamber is maintained at 100^{o}C for 30 minutes for full dehydration of sample. Mass loss due to evaporation at this stage is 28%. In the third stage, temperature rises from 100^{o}C to 600^{o}C at 20 ^{o}C /min heating rate. Changes in weight of the foliage sample is measured with the increase in temperature. Curves of mass fraction and reaction rate against temperature are plotted in Figure 2**.** Temperature of peak reaction rate (0.0016 s^{-1}), also known as reference temperature, is found to be 332^{o}C. Mass residue after heated to 600^{o}C is 20.8%, also being the rate of char [14]. Pre-exponential factor A and activation energy E are calculated to be A= 11.68 s^{-1}, E=39730 K. Heat of combustion is determined to be 13MJ/kg. Such pyrolysis mechanism is shown in Figure 3. Pinus Sylvestris Needle is considered as a mixture of wood components, simplified as cellulose, and moisture content. When exposed to heat, dehydration first takes place, and then cellulose degrades to form 79.8% of volatiles and 20.2% of char, derived from TGA. Properties of char, including specific heat, conductivity and density are taken from the literature [10]. Surface volume ratio, 2550 m^{-1}, is calculated from bulk density and molecular mass of Pinus Sylvestris Needle. Rate of spread in level set model is set to be 0.0017m/s, which is observed from live experiments.

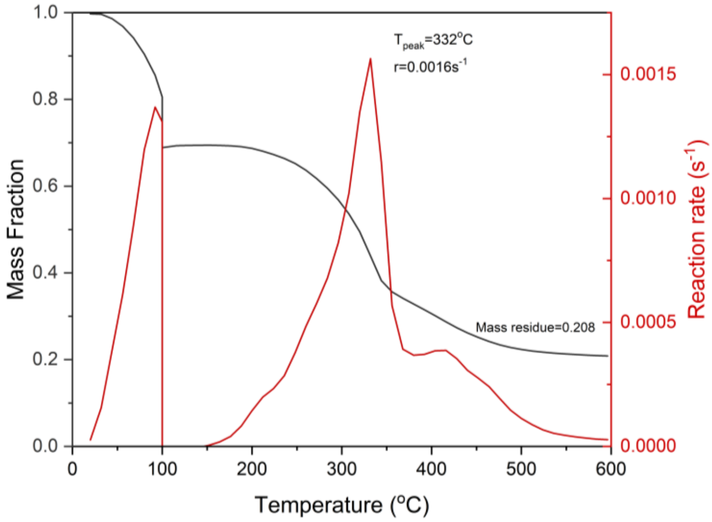

Figure 2 TG-DTG curves of the pyrolysis process of foliage sample.

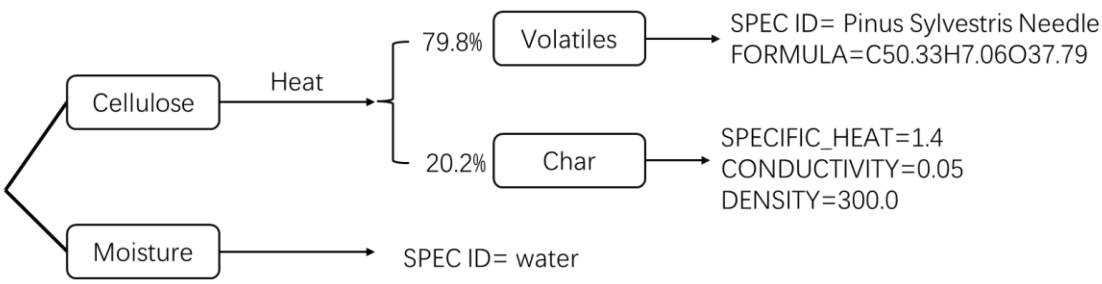

Figure 3 Mechanism of Pinus Sylvestris Needle decomposition.

FDS, version 6.8.0, developed by NIST is chosen for computational simulations, Level set model is an empirical model that does not solve any pyrolysis mechanism. This method is derived from the Rothermel-Albini surface fire spread rate formula [10]. It is assumed that a surface fire spreading from a point under certain wind, slope and vegetation conditions has an elliptical fire front of a fixed length-to-breadth ratio. Level set model helps to save time costs of simulation; hence it is regarded as useful for large scale WUI fire simulation. A Very Large Eddy Simulation (VLES) mode was applied for flow calculations. The domain of the model is set to be $0.6m \times 0.2m \times 0.2m$, with grid size $0.005m \times 0.005m \times 0.005m$. Needle sample is simulated as a homogeneous fuel bed sizing $0.6m \times 0.2m$. The fuel depth and fuel load are defined as 0.035m and 0.3 kg/m^2 respectively. Bunsen burner is defined as the ignition source with surface temperature 1500°C. Ignition source is applied at one end of fuel bed for 10 seconds and then removed. Six thermocouples (bead diameter = 0.0015 m), one radiant and one convective heat flux meter are used. Exact position of each device is demonstrated in Figure 4.

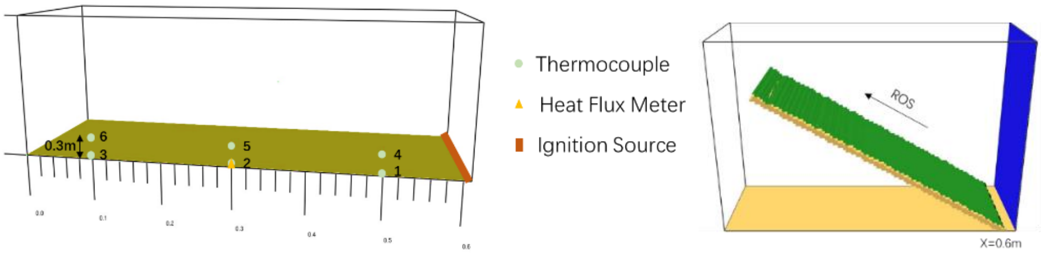

Figure 4 Numerical set up under 0º (left) and 30º slope (right).

Simulation results of 28% moisture content under no wind conditions at 0º and 30º slope is compared with experiment recordings in terms of temperature reading and rate of spread. 9 simulations are run in total. Three moisture content level, 6%, 11% and 28%, combined with two wind conditions, no wind and 3.5 m/s wind at 0º slope are simulated, as well as the same three moisture content level with no wind at 30º slope angle.

3. Result and Analysis

Figure 5 exhibits temperature readings of thermocouples generated by simulation compared to experiments under no wind no slope condition and no wind 30º slope condition. At 0º slope angle, the trend of change in temperature fits well with experiment results. For TC1 and TC2 (bottom ones), the time of occurrence of temperature peak is well predicted, though the peak values are underpredicted by 20.7% and 9.4% respectively. In numerical results, temperature peaks of TC4 and TC5 (top ones) occur earlier than that during experiments. Also, numerical results of maximum temperature as recorded by TC4, 53ºC is underpredicted as experimental maximum temperature recorded by TC4, is 214ºC. No substantial increase in temperature is recorded during experiments in TC3 and TC6 (farthest ones from ignition source) and there is a similar trend during simulations. Numerical data at 30ºC slope indicate that fire propagates much faster, 0.0063 m/s, compared to experiments, 0.0026 m/s. Similarly, temperature peaks occur earlier than that in experiments.

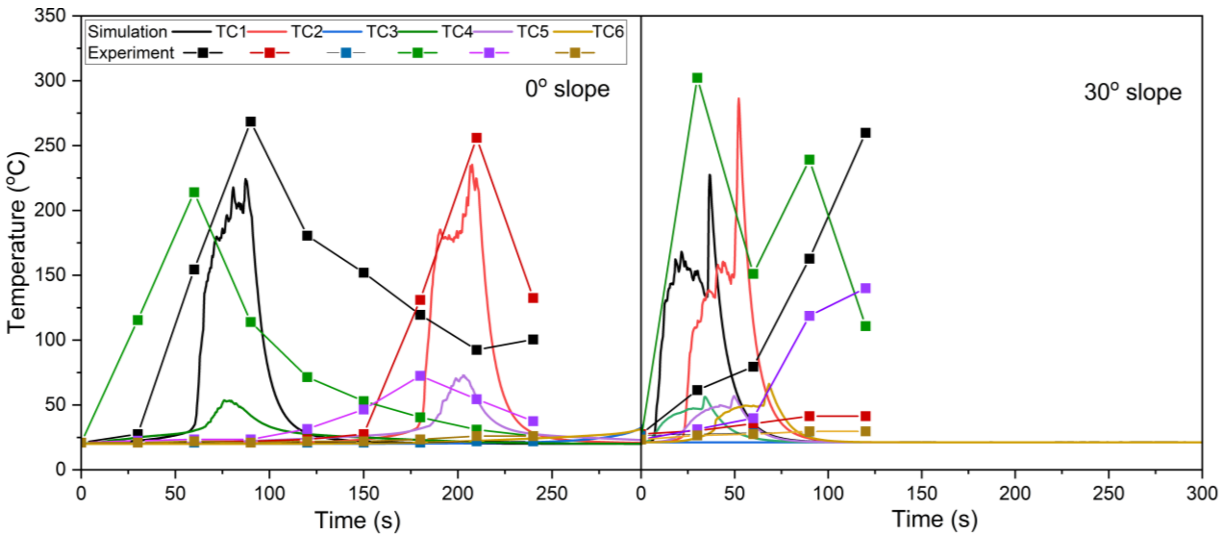

Figure 5 Temporal evolution of experimental and numerical temperature readings under no wind 0ºslope (left) and 30º slope (right).

As shown in Figure 6, at 0º slope angle, ROS keeps consistent at 0.0017 m/s under both wind conditions (W0S0 and W3S0) and three moisture content levels. An increase takes place when fuel bed is inclined to a 30º slope angle. Under inclined conditions (W0S30), the effect of moisture also becomes more obvious as ROS decreases from 0.0076 m/s to 0.0065 m/s when moisture content increases from 6% to 28%.

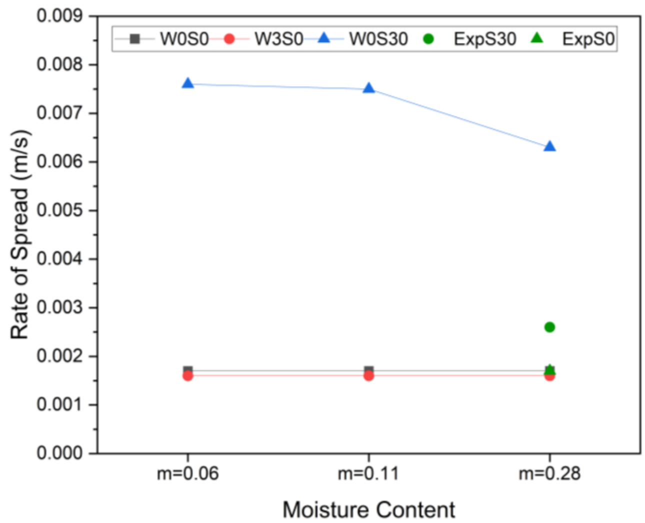

Figure 6 Numerical and experimental data of ROS at three moisture content levels.

Under no wind and no slope condition, no obvious change is observed in temperature reading with the increase of moisture content level both in terms of time of peak occurrence and peak values, see Figure 7 left. TC1 of all three simulations reaches around 219 ºC at 88 seconds. As the fire propagates, at 208 s, readings of TC2 reach their peaks at around 243 ºC. At no wind conditions, application of slope angles increases the temperature peak of thermocouple1 at all moisture content level from around 224 ºC to 233 ºC, see Figure 7 middle. Due to faster fire propagation, temperature measured by TC1 starts to increase earlier at 30º slope angle, reaching the peak at about 36s. Figure 7 right displays the effect of wind at 0º slope. At all three moisture content levels, curves of temperature shift to the left representing a sooner heat transfer when additional 3.5 m/s wind is applied. However, the peak values almost remain unchanged.

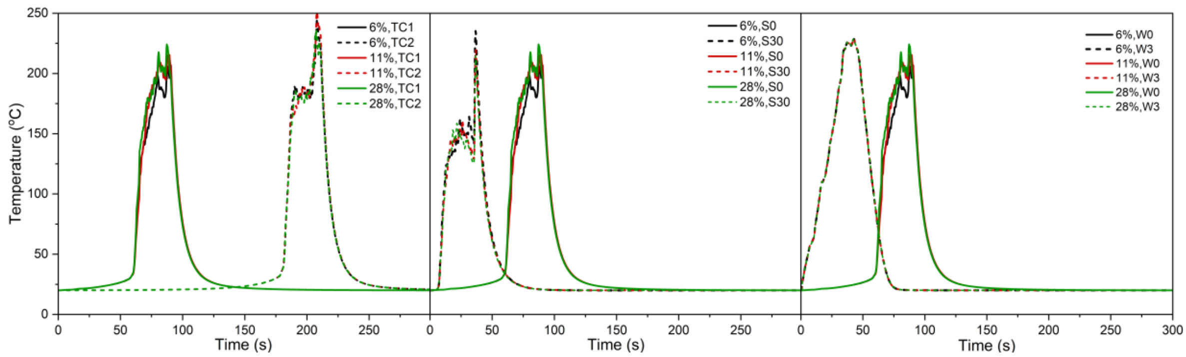

Figure 7 Temporal evolution of temperature from TC1 and TC2 under no 0º slope for three moisture content levels, 6%, 11% and 28% (left). Temporal evolution of temperature of TC1 under no wind condition with two slope angles, 0º (S0) and 30º slope (S30), and three moisture content level (middle). Temporal evolution of temperature of TC1 at 0º slope with two wind conditions, no wind (W0) and 3.5 m/s wind (W3), with three moisture content level (right).

4. Conclusions

In this study, experiments are carried out at medium scale, $0.6m \times 0.2m \times 0.2m$, to investigate how fire propagates on a Pinus Sylvestris Needle fuel bed of 0.035m fuel height and 0.3 kg/m^2 fuel load, which represents a surface fire. Data is collected for model validation, including temperature reading and travelling speed of flame front. TGA method is applied to generate fuel properties of Pinus Sylvestris Needles. Output of TGA is analysed and provides a basis for simulation as input parameters. FDS is chosen to be the CFD tool for this study. Model is established to have the same set up and same fuel properties as in the experiments. Level set model is used for computational simulation. Numerical data involving temperature reading and ROS, is compared with those recorded in experiments. Comments are made on the accuracy of simulations under no wind no slope and no wind 30° slope conditions. Effect of moisture content, wind and slope is studied using numerical method. Increase of moisture content from 6% to 28% slows down the fire propagation at 30° slope. However, this trend doesn't appear in simulations on 0° slope, no matter at 0m/s or 3.5m/s wind conditions. Application of wind and slope may increase the fire intensity. 3.5m/s wind in the direction of fire spread enables a sooner increase in temperature reading of thermocouple while maintaining the peak values. An inclined slope angle of 30° brings the occurrence of temperature increase value forward, also increasing the peak reading of temperature.

For future study, more experiments will be carried out under different environment conditions for better validation of model. Domain of simulation could be enlarged to large scale. Intervals of temperature readings from thermocouples in experiments should be reduced to 0.1 s or even less.

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