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Experimental measurements and numerical modeling of marginal burning in live chaparral fuel beds

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Abstract

An extensive experimental and numerical study was completed to analyze the marginal burning behavior of live chaparral shrub fuels that grow in the mountains of southern California. Laboratory fire spread experiments were carried out to determine the effects of wind, slope, moisture content, and fuel characteristics on marginal burning in fuel beds of common chaparral species. Four species (*Manzanita* sp., *Ceanothus* sp., *Quercus* sp., and *Arctostaphylos* sp.), two wind velocities (0 and 2 m/s), two fuel bed depths (20 and 40 cm), and three slope percents (0%, 40%, or 70%) were used. Oven-dry moisture content M of fine fuels (<6.25 mm diameter) ranged from 29% to 105%. Sixty-five of 115 fires successfully propagated the length (2.0 m) of the elevated fuel bed. A previously derived empirical marginal burning criterion was assessed, and a suitable modification was proposed for live chaparral fuels. Based on the experimental data, a stepwise logistic regression model was developed to predict the probability of successful fire spread. This procedure resulted in the selection of wind speed, slope percent, fuel loading, fuel moisture content, and relative humidity as the primary variables. It correctly classified 96% of 115 fires. Finally, a multidimensional numerical model for vegetation fire spread using a porous media sub-model was developed to simulate the laboratory fires. Results are used to analyze the internal heat transfer and combustion processes that determine fire spread success in shrub fuel bed.

Keywords: Fire spread; Marginal burning; Chaparral; Fuel bed

1. Introduction

Knowing when fires will spread and when they will not in live shrub fuels, such as chaparral in California, is important for fire behavior modeling and is particularly useful for those working with prescribed fire. Marginal burning refers to conditions under which the fire either spreads, usually a desired outcome for a prescribed burn, or simply peters out after ignition. Prescribed fire is often used to manage living fuels and prevent potential wildfire hazard build-up by selecting conditions resulting in marginal burning. The advantage is that it results in low-intensity fires that can be controlled relatively easily. In California, several tools are used by fire managers to aid in the use of prescribed fire in chaparral. BEHAVE [1] and FIRECAST [2], both computer implementations of the Rothermel spread model [3], are used to estimate fire behavior under various weather settings. The matrix approach [4] links a quasi-quantitative description of fire behavior and effects to a score computed from severity points assigned to various values of fuel

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and weather variables. Both the matrix approach and the Campbell Prediction System [5] utilize basic understanding of the variables that influence fire behavior to arrive at predictions.

Despite the availability of several models, our ability to predict when fire will spread in living chaparral fuels is still limited by two factors: (1) current fire spread models were designed primarily for dead, not living, fuels and (2) only a limited set of experimental data on marginal burning in live fuels exists, thereby precluding the development and testing of models. From a fire behavior perspective, the primary difference between live and dead fuels relates to moisture content. In the case of dead fuels, it is strongly dependent on environmental temperature, humidity, and precipitation. Fuel moisture in live fuels is regulated by biological processes and is relatively insensitive to environmental conditions. Other differences exist in biological structure and chemical composition; for example, live fuels have more high-energy extractives such as waxes, oils, terpenes, and fats. In the US, limited modeling of fire spread in live fuels has occurred [2,6,7].

Prescribed fire in chaparral is typically attempted when fuel moistures are higher in most cases than when wildfires occur [8]. This occurs in the spring and early summer following the winter growing season or in late fall and early winter when the plants have emerged from summer dormancy and have begun growth. Burning conditions are often marginal, and there is a threshold between no fire spread and successful propagation. Others have reported thresholds in fire behavior as influenced by various fuel and environmental variables [9,10]. The factors that influence these thresholds might be understood by successful prescribed fire managers in chaparral, but no systematic experiments have been conducted to describe these threshold conditions.

The Rothermel model [3] was derived based on several simplifying assumptions. Fuels are assumed to be uniform, dominated by dead material, and in close proximity to the ground. The model assumes fire spread in the absence of wind and slope. Wind and slope function as multipliers to the rate of spread. The model does not predict the rate of spread when wind is required for successful spread [11]. Furthermore, fire spreads successfully in chaparral fuels at higher fuel moistures than most of the experimental data used to develop the Rothermel model. Wilson [12,13] examined fire spread in moist fuel and proposed changes in the manner in which moisture content is modeled in the Rothermel model. As part of this work, Wilson [13] developed a "predictive rule of thumb" to determine if fires would burn in wooden fuel beds. The rule of thumb was that a fire would rarely burn if

$$M > 0.25\ln(2\sigma\beta\delta), \quad (1)$$

where M is the moisture content, measured as fraction of oven-dry weight, and σ, β, and δ are the fuel particle surface area-to-volume ratio, fuel bed packing ratio (solid fuel volume to total fuel bed volume), and fuel bed depth, respectively. This rule of thumb was developed using data from fuel beds constructed of shaved excelsior or milled wood sticks with M ranging from near oven-dry up to fiber saturation (30%). The applicability of this model to live chaparral shrub fuel beds is currently unknown.

Given that current operational models do not adequately model fire spread in chaparral fuels and that data describing marginal burning conditions in chaparral do not currently exist, we have embarked upon an experimental effort to determine the important fuel and environmental variables that determine propagation success in laboratory-scale fires in common chaparral fuels. A logistic model to predict the probability of successful fire spread is developed using stepwise logistic regression. Ten predictor variables were considered in the logistic equation: species, slope, moisture content, wind velocity, fuel bed depth, packing ratio, relative humidity, ambient temperature, fuel loading, and fuel orientation (horizontal, vertical).

A multidimensional numerical model for vegetation fire spread using a porous media submodel was developed to simulate the laboratory fires [14]. The advantage of a numerical model is that the detailed velocity, temperature, and species concentration field at each time step can be obtained, and the internal combustion mechanism and various heat transfer processes of radiation, convection, and conduction can be explicitly described [15,16]. These results are used to analyze the effect of some important fuel and environmental variables that determine fire spread success.

2. Methods

2.1. Experimental details

The effects of wind, fuel moisture content, fuel bed depth, fuel bed packing ratio, slope, and environmental conditions on fire spread success in live chaparral fuels were investigated in a series of 115 experimental fires carried out between 1/2003 and 9/2003. Fuel beds (2 m long, 1.0 m wide, and of various depths) were constructed of branch and foliage material collected from living chaparral growing at an elevation of 1160 m in an experimental area 50 km east of Riverside, CA. Branches (<0.64 cm) from manzanita (*Arctostaphylos parryana*), chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolius*), and scrub oak (*Quercus berberidifolia*) plants comprised the fuel. These common, highly flammable shrub species grow in the mountains of southern California and throughout the Coast Ranges. Fuel was collected in the morning so as to minimize moisture loss through transpiration. Dead fuel was carefully discarded to the extent possible. The fuel was then bagged and transported to the burn facility at the Forest Fire Laboratory. For the experiments from 1/16/2003 to 2/7/2003, the live fuel was stored in a large refrigerator and burned within the next day. Fuels collected after 2/2003 were burned on the day of collection to reduce moisture loss.

The fuel beds were elevated above the surface of a tilting platform by 40 cm to simulate an aerial fuel (Fig. 1). Air could be entrained from the both ends of fuel bed; air entrainment from the lateral sides of the fuel bed was prevented by metal sheeting. Fuel was uniformly distributed to the greatest extent possible. Fires were ignited from one side in a 50 cm section along the length of the live fuel bed (Fig. 1). Between 300 and 400 g of excelsior and a small amount of isopropyl alcohol were uniformly added to the ignition zone to initiate and sustain ignition. The slope percent was modeled by raising one side of the tilting platform. Air flow to simulate wind was induced using three rotary box fans that were turned on simultaneously. Only two conditions "wind" and "no wind" were considered. The average velocity measured by hotwire was 2 m/s. A fire spread was described as successful if the live brush ignited from the burning zone and then propagated the length of the 2 m fuel bed, else it was declared unsuccessful. Temperature signals from thermocouples placed in the fuel bed were utilized to compute fire spread rate in the case of successful fire spread. All fire tests were also video recorded for fire spread analysis.

Fig. 1. Fuel bed constructed of live foliage and branches of chamise with 2.0 m long, 1.0 m wide, and 0.4 m depth. The fire illustrates the initial ignition.

2.2. Statistical analysis

Because the response variable (spread success) was binary, a logistic regression method was used to develop a model to predict spread success [17]. The logit, $\log[p/(1-p)]$, of the probability, $p(x) = \mathbf{Pr}(\text{spread} = \text{Yes}|\mathbf{x})$, of spread success was set equal to a linear function $\mathbf{X}\Theta = \theta_0 + \theta_1 x_1 + \cdots + \theta_n x_n$ of the predictor variables $(x_1, \ldots, x_n)$ and the parameter estimates $(\theta_0, \theta_1, \ldots, \theta_n)$ that were determined by maximum likelihood estimation. The regression model and an expression for the probability p are given by:

$$\begin{aligned} &\log[p/(1-p)] = X\Theta, \\ &\Pr(\text{spread} = \text{Y}) = \mathrm{e}^{X\Theta}/(1+\mathrm{e}^{X\Theta}). \end{aligned} \tag{2}$$

Stepwise logistic regression was used to select the fuel bed and environmental variables to predict fire spread success.

2.3. Computational modeling

A numerical model for vegetation fire spread was developed to simulate the present experimental fires. In this work, we considered a two-dimensional unsteady flow with density-weighted averaged governing equations for flow velocity components (u, v), energy, and chemical species mass fraction (moisture, wood pyrolysis fuel gas, oxidizer, and products). The eddy viscosity associated with turbulent fluxes was evaluated from the turbulent kinetic energy k and its dissipation rate $\varepsilon(k-\varepsilon$ model). Pyrolysis fuel gas combustion is described by the eddy-dissipation model of Magnussen and Hjertager [18]. An extension of the discrete ordinates (DO) method to porous media was developed to calculate the radiative heat transfer between gas and solid phases. Soot formation is described through the evolution of the average soot volume fraction accounting for nucleation, surface growth, and oxidation processes. The generic governing equations of momentum, energy, and species mass fractions are discretized using an implicit method. The pressure and velocity coupling is treated using a SIMPLER method [19]. For no wind condition, open boundary conditions exist at the surrounding surfaces. At the boundary, outflow or inflow conditions were assumed to be zero derivatives for all the variables. A grid resolution study indicated that a non-uniform grid of 127×65 cells, covering the computational domain of 4.0 m length by 3.0 m height, was adequate. The vegetation fuel bed was 1.3 m long by 0.4 m height (or variable height) with 51×16 cells of uniform size. Additional modeling and computational details can be found in [14,15].

A successful fire spread occurs when sufficient energy is transferred from the flame front to the unburnt solid fuel, resulting in an increase in the fuel temperature to its ignition point. The solid phase temperature is the result of interacting radiative, conductive, and convective heat transport through the solid matrix, and between the solid and the gas. In addition, water vaporization, pyrolysis, and fuel combustion also influence the solid phase temperature. Because of the endothermic process of water vaporization ($Q_{vap} = -2250$ kJ/kg) and high moisture specific heat ($c_p = 1.858$ kJ/kg-K, at temperature $T_0 = 300$ K), the moisture content included in the solid phase plays a significant role on fuel ignition delay.

Fig. 2. Foliage and fine branch samples of four chaparral species used in marginal burning experiment: (1) scrub oak (*Q. berberidifolia*), (2) manzanita (*A. parryana*), (3) chamise (*A. fasciculatum*), and (4) hoaryleaf ceanothus (*C. crassifolius*). A one-cent coin is used to show the size.

3. Results and discussion

3.1. Description of data set

Sixty-five (or 56%) of the 115 tests resulted in successful fire spread. Chamise is the fuel in most of the tests completed (66 of 115) (Table 1). Fuel moisture content of samples burned on the day of collection ranged from 53% for chamise to 106% for manzanita. Chamise fuel moisture was 80% on 3/7/2003, 91% on 5/9/2003, 77% on 7/2/2003, and 53% on 9/11/2003, which indicated that new growth occurred between 3/7 and 5/9, and the new growth was drying out by 9/11—a typical annual trend in live fuel moisture in chamise. Manzanita, ceanothus, and scrub oak exhibited the change in fuel moisture content similar to chamise. The environmental temperature increased from 18 °C in January to 38 °C in July and then decreased to 32 °C in September. The relative humidity decreased from 70% in January to 20% in May and then increased to 36% in September.

Table 1
Summary of fire spread success in live chaparral fuels

Variable	Value	Fire spread success	
		No	Yes
Species	Ceanothus	7	13
	Chamise	24	42
	Manzanita	12	7
	Scrub oak	7	3
Slope (%)	0	40	43
	27	3	6
	40	5	7
	70	2	9
Fuel bed depth (cm)	20	29	22
	40	21	43
Wind velocity (m/s)	0	42	30
	2	8	35
Total number		50	65

Of the tests performed to date, wind was required in half of the fires for successful spread (Table 1). Because several experimental variables were examined in conjunction, care should be taken in identifying data trends from Table 1. For example, the 24 chamise fires that did not spread had different slope percents, fuel bed depths, and wind velocities.

In the experiments reported here, the physical fuel properties varied between species, but were assumed constant within a species. The exception to this is moisture content. Manzanita, scrub oak, and ceanothus are all species with leaves that are generally ovoid in shape (Fig. 2). The leaf thickness varied between species, with manzanita having the thickest leaves and scrub oak having the thinnest. In contrast, chamise leaves are linear in shape. By changing the fuel loading and the fuel bed depth, the fuel bed has different packing ratios that range from 0.008 to 0.025. The experimental uncertainties come from the varied effects of fuel samples, environmental temperature and relative humidity, and fuel packing in the fuel bed, etc. It would be reduced by repeated experimental tests.

3.2. Wilson's rule applied to live fuels

In Wilson's rule (Eq. (1)), the product $S = \sigma\beta\delta$ represents the total fuel surface area per unit horizontal area of fuel bed [13]. Heat transport out of the combustion zone, heat absorption by fuel particles, moisture transport into and out of fuels, production rates of volatile combustibles by pyrolysis, diffusion of air, effects of wind, and so forth, are all related to fuel surface area. It is expected that fires would be more likely to burn at higher fuel moisture M for larger S.

Table 2
Validation of Wilson's rule for fire spread success in chamise fuel beds

Number	M	Ω	Experiment	Prediction	T_0 (°C)	Humidity (%)	Wind (m/s)	Slope (%)
1	0.299	0.814	Y	Y	18.7	72	0	0
2	0.385	0.630	N	Y	18	70	0	0
3	0.385	0.807	Y	Y	18	70	0	0
4	0.637	0.756	N	Y	19	75	0	0
5	0.804	0.787	N	N	20	77	0	0
6	0.799	0.787	N	N	25	74	0	0
7	0.795	0.787	N	N	25	74	0	0
8	0.909	0.613	N	N	22	30	0	0
9	0.767	0.810	N	Y	37.6	25	0	0
10	0.654	0.827	Y	Y	37.4	22	0	0
11	0.606	0.784	Y	Y	37.1	30	0	0
12	0.532	0.834	Y	Y	35.2	29	0	0
13	0.532	0.673	Y	Y	35.2	29	0	0
14	0.804	0.787	Y	N	20	77	2	0
15	0.909	0.613	Y	N	22	30	2	0
16	0.799	0.787	Y	N	25	74	0	40
17	0.804	0.787	Y	N	20	77	0	70

Because the effects of wind, slope, high moisture content of live fuels, and environmental conditions were not considered, the applicability of Wilson's rule to chaparral fuel beds has not been previously examined. We selected 17 experimental fires in chamise fuel beds (Table 2, in which $\Omega = 0.25\ \ln(2\sigma\beta\delta)$) for analysis. For the purpose of validation, experimental runs 1–13 (Table 2) were conducted under no wind and zero slope conditions similar to Wilson [13]. From Eq. (1), the fire will not spread if M is larger than Ω. Of the 13 fires, Wilson's rule correctly predicted 10 outcomes (77%). For the no wind and no slope fires, the environmental temperature and relative humidity were variable. Comparison of runs 4 and 13, in which M is smaller than Ω, shows that one fire spread (run 13) and the other did not. This could be a result of experimental variation or due to warmer, drier environmental conditions under which run 13 was conducted. For four chaparral fuel beds under no wind and no slope conditions, the experimental observations from 45 tests show that fire rarely burns if the ratio of M:Ω is larger than 0.82. Based on these results, we propose a correction to Wilson's rule for live chaparral fuel that a fire would rarely burn if

$$M > 0.2\ln(2\sigma\beta\delta). \tag{3}$$

Two additional factors that influence fire spread but were not considered in Wilson's rule are wind and slope. For runs 14 and 15 (Table 2), although M (0.804 and 0.909) is larger than Ω (0.787 and 0.613), fire spread was successful in the presence of wind. Similarly, fires spread successfully for runs 16 and 17 in the presence of slopes of 40% and 70%, respectively. However, Wilson's rule suggested that fire would not spread successfully.

Wilson's rule focuses on the effects of fuel moisture and geometric properties of fuel beds on marginal burning. Although some important factors are not included, it is a good starting point to analyze the parameters that influence marginal burning of live chaparral fuel. By increasing the values of σ, β, and δ, the fire can be ignited with higher probability. For live fuel, the value of σ is usually a constant. Variables β and δ are related to the fuel arrangement, and fuel loading, Fl (fuel weight per unit horizontal area of fuel bed), calculated as $Fl = \beta\delta\rho_f$, where ρ_f is the fuel particle density. For the same fuel, higher fuel loading implies larger packing ratio or higher fuel bed depth. We have conducted a series of fire tests to examine the effects of β and δ.

Designating two test groups A and B, for the same fuel loading and other conditions, group A has $\beta = 0.0125$ and $\delta = 40$ cm, while group B has $\beta = 0.025$ and $\delta = 20$ cm. Each group includes three test cases. Results show that all fire burning cases in group A are successful. In group B, only one is not successful. This suggests that fuel loading is an important variable in determining fire spread success. However, a larger packing ratio leads to less diffusion of oxygen to fuel. This makes the observed fire spread rate of group B (0.089 m/min) smaller than that of group A (0.106 m/min).

3.3. Results of logistic regression analysis

Of the 10 predictor variables considered in the logistic equation, the stepwise regression method resulted in the selection of five variables by choosing the variable with the largest χ^2 [17] to predict the probability of fire spread success. Three of the variables were environmental (wind speed, slope, and relative humidity) and two were fuel (dry fuel loading and moisture content) variables. The selection of dry fuel loading as a predictor variable is consistent with Wilson's rule.

It is interesting to note that both relative humidity and fuel moisture content were selected. For dead fuels, moisture content responds passively to changes in atmospheric temperature and humidity. Relative humidity and dead fuel moisture content would be highly correlated, and the assumption of independence of the variables would be suspect. The live fuels we are studying actively regulate their moisture content. It is currently not known if changes in relative humidity affect the processes the plants use to regulate their moisture content. Since the fuels were cut, they were unable to regulate their moisture content; however, the predominant process that occurred between sample collection and burning was moisture loss.

The equation that resulted from the stepwise logistic regression is

$$X\Theta = 13.225 + 5.49WS + 0.2SL + 3.12DFL - 0.11RH - 0.29M, \quad (4)$$

where WS is the wind speed (m/s), SL is the slope percent (%), DFL is the dry fuel loading (kg/m^2), RH is the relative humidity (%), and M is the live fuel moisture content (%).

The relative sensitivity of fire spread to each of the predictor variables can be found by examining the odds ratio. The odds ratio describes the change in risk of fire spread that is associated with a change in the predictor variable. The calculated odds ratio from logistic regression method for WS is 242.58, but less than 22.61 for other variables. This indicates the extreme importance of wind speed to risk of fire spread for these data. We can use this logistic model to test a fire spread case. For experimental run 10 in Table 2, $WS = 0$, $SL = 0$, $DFL = 3.325$, $RH = 22$, $M = 65.4$, and fire spread is successful. From Eq. (4), $X\Theta = 2.21$, and the probability of fire spread success is 90.1% (Eq. (2)). Similarly, for experimental run 9 in Table 2, $WS = 0$, $SL = 0$, $DFL = 3.113$, $RH = 25$, and $M = 76.6$, resulting in no fire spread. The estimated probability of successful fire spread is 11.3%. These results are in excellent agreement with the experimental observations.

For experiments from January 2003 to September 2003, the relative humidity decreased as environmental temperature increased. It is well known that relative humidity and air temperature are correlated for a constant air mass. If environmental temperature is used as a predictor variable, the fitted logistic equation is,

$$X\Theta = -0.585 + 5.62WS + 0.17SL + 2.72DFL + 0.27TE - 0.25M, \quad (5)$$

where TE (°C) is the environmental temperature. Both fitted models (Eqs. (4) and (5)) correctly classified nearly 96% of the 115 fires in the data.

3.4. Computational modeling results

Using the computational model described in Section 2.3, we have simulated the fire experiments for a variety of conditions. The experimental runs 2 and 3 are chosen for illustration to further analyze marginal burning condition. The surface area-to-volume ratio is $\sigma = 2300$ m^{-1}, an averaged value from the samples [20]. The packing ratio is $\beta = 0.01$ that was calculated from the fuel loading and the fuel density of $\rho_f = 560$ kg/m^3. The fuel type and packing ratio were equivalent for both runs. The fuel bed depth differed ($\delta = 20$ cm for run 2 and $\delta = 40$ cm for run 3); fuel loading of run 3 ($Fl = 4.2$ kg/m^2) was double the fuel loading of run 2. Run 2 did not result in fire spread while run 3 did. The time evolution of the calculated pyrolysis gas (CO) contours from ignition to extinction for conditions corresponding to run 2 illustrates fire spread failure (Fig. 3A, $\delta = 20$ cm), consistent with the experimental result. The amount of fuel gas due to pyrolysis decreased with time; a successful fire spread would have a constant rate of production of pyrolysis gas after ignition as shown in Fig. 3B ($\delta = 40$ cm) for run 3. For the same packing ratio, increasing fuel bed depth or fuel loading will result in an enhanced probability of fire spread success. At this point, the numerical results are in good agreement with the experimental observations. The spread rate approximated from the time evolution of pyrolysis gas is 0.2 m/min, which is in good agreement with the observed experimental fire spread rate of 0.17 m/min.

To further understand the relationship of heat transfer and fuel combustion on marginal burning, the time evolution of solid phase temperature, and accumulated heat absorbed by solid particles in a computational cell are illustrated in Fig. 4. It corresponds to a successful fire spread case for $\delta = 40$ cm. These heat transfer contributions, Q_{conv}, Q_{rad}, and Q_{mass}, are convective heat flux between the gas phase and the solid, radiative heat flux, and heat release due to water vaporization, pyrolysis, and fuel combustion, respectively. To ignite fuel, a solid particle needs sufficient heat energy. In the preheat region (time from 0 to 26 s), the most effective energy source is radiative heat transfer, Q_{rad}. The solid particle temperature increases but at a relatively low rate. The thermochemical contribution, Q_{mass}, remains negative due to water vaporization. Due to a 20 cm separation distance with the ignition zone, the temperature of gas phase is lower than that of solid phase, which leads to a negative convective heat. When the fire front is close to the observation point, Q_{rad} continues to increase steadily, however, Q_{conv} rises dramatically. This leads to a rapid increase in solid phase temperature from about 450 to 1200 K in a short time. This implies that the fuel particle is ignited. In the ignition zone, due to

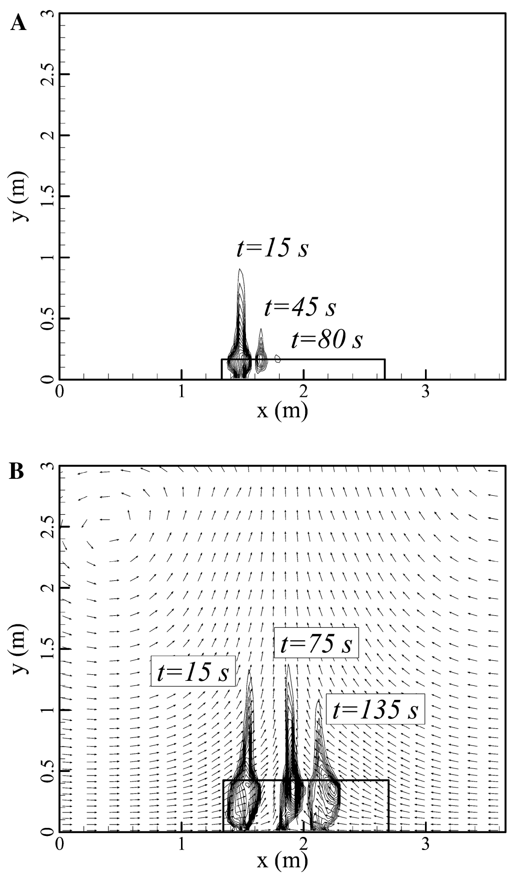

Fig. 3. Time evolution of calculated pyrolysis gas (CO) contours: (A) fuel bed depth is 20 cm, and the fire spread is failure; (B) fuel bed depth is 40 cm and the fire spread is successful, and vectors denote the velocity directions at $t = 75$ s with a maximum speed of 5 m/s. The rectangular frame denotes the fuel bed.

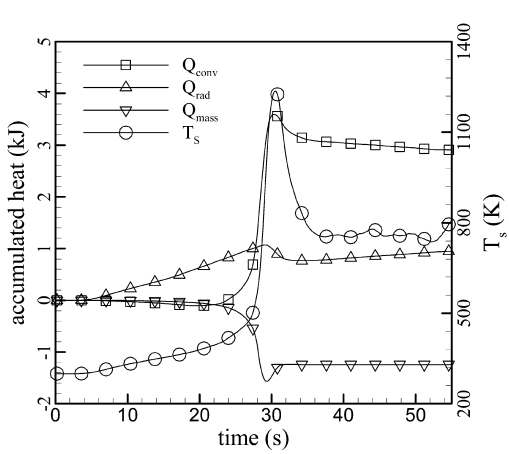

Fig. 4. Time evolution of solid particle temperature and accumulated heats absorbed by solid particles in a computational grid cell, which is located initially at a distance of 20 cm downwind from the ignition zone.

increase of solid particle, more water is vaporized. There is a sharp decrease in Q_{mass}. After ignition, due to high temperature, the solid phase losses heat by Q_{rad} and Q_{conv}, and solid temperature decreases. On the other hand, due to the heat of char combustion, which compensates for losses from water vaporization and pyrolysis processes, the solid particle temperature remains constant at about 750 K.

Analyzing the unsuccessful fire spread case of $\delta = 20$ cm results show that there is not enough energy of Q_{conv} and Q_{rad} to compensate the losses of Q_{mass}, especially at the time of ignition. An increase in fuel loading means more energy can be transferred to the unburned region. Similarly, wind and slope enhance Q_{conv} and Q_{rad}, and increase the probability of fuel burning. Conversely, high moisture content stops fuel burning because of the heat loss due to water vaporization.

4. Conclusion

Current fire spread models do not adequately model the transition between no spread and spread in live fuels. We have conducted 115 experiments to determine the importance of fuel and environmental variables on fire spread success for four different species of chaparral in the laboratory. In examining the applicability of a modified Wilson's rule to marginal burning of live chaparral fuel, it was found this rule can give reasonable results for some cases but needs to include more environmental variables. Using a stepwise logistic regression method to analyze these 115 fires, a stepwise logistic regression model was developed to predict the probability of fire spread success. Five variables, viz., wind, slope, dry fuel loading, fuel moisture content, and relative humidity (or environmental temperature), were selected by the model. Analyses indicated the importance of wind speed on fire spread success. The laboratory fires were simulated using a two-dimensional multiphase model. Numerical results are consistent with the experimental observations. The simulated heat transfer processes and combustion mechanism in the fuel bed are helpful for us to understand the factors that determine fire spread success.

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Comment

Oleg Korobeinichev, Russian Academy of Sciences, Russia. Could you please comment on whether kinetics and product composition of chaparral fuel pyrolysis were used for modeling of their combustion?

Reply. In this paper the numerical model was used primarily as an exploratory tool to analyze the experimental results and gain a better understanding of various heat transfer mechanisms. At the present time there is no accurate model for pyrolysis of chaparral fuel; the kinetic parameters of the rate and product composition are taken from the model of Porterie et al. ([15], in the paper) for pine needles.