P5.5 EXPERIMENTAL STUDY ON FIRE BEHAVIOR OF LIVE CHAPARRAL FUELS

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ABSTRACT

Wildfire spread in living vegetation, such as chaparral in southern California, often causes significant damage to infrastructure and ecosystems. A physically-based semi-empirical model to predict surface fire spread rate is used in the United States to assist in a variety of fire management operations. However, the applicability of this model to shrub fuel beds such as live chaparral is currently unknown. In order to study wildfire spread in living vegetation, four common chaparral shrubs--chamise, manzanita, scrub oak and ceanothus were burned and compared. The observed fire behavior included mass loss rate, flame height, temperature structure and velocity field above the burning fuel bed. It was observed that flame height increases mainly with heat release rate. Temperature structure of the fire plume was measured by an IR-camera and a simple Gaussian profile was fit to describe temperature variation in the radial direction.

1. INTRODUCTION

Periodic fire has been a part of the southern California landscape for centuries. The mountain slopes surrounding the Los Angeles basin are covered at lower elevations (below 1600 m) with chaparral vegetation characteristic of Mediterranean climates (Philpot 1977). Studies of fire spread mainly under laboratory conditions with simplified wooden fuels over many years have produced good quantitative descriptions (Fons et al. 1963; Rothermel 1972; Wilson 1982 and 1990; Albini 1967 and 1985). Rothermel and Philpot (1973) applied Rothermel's model to chaparral and Albini and Stocks (1986) tested Albini's 1985 model with jack pine (*Pinus banksiana*) crown fire data. However under natural conditions, free-burning wildfires are not only unplanned and unexpected but occur in many different and complicated situations. For predicting fire spread rate, existing operational models utilized by the Forest Service are based on the semi-empirical model developed originally by Rothermel (1972). It is applicable to quasi-steady burning of surface fires with uniform fuel loading and assumes that the fuel is dominated by dead material and in close proximity to the ground. Crown fire, transition from ground-to-crown-fire, fire spread through live fuels, fire spread by spotting, and modification of meteorological conditions by the fire are some of the phenomena not accounted for in the Rothermel model. Wilson (1982, 1985 and 1990) suggested addition of a term in the spread model involving wind and fuel moisture. However, the application of this to shrub fuel beds such as chaparral is currently unknown. Chaparral is a fire-prone, shrub dominated plant community characterized by evergreen sclerophyllous shrubs such as chamise (*Adenostoma fasciculatum*), manzanita (*Arctostaphylos parryana*), scrub oak (*Quercus berberidifolia*) and hoaryleaf ceanothus (*Ceanothus crassifolius* (Fig. 1 and Fig. 2). Usually two or more species are mixed and can be found in the foothills of southern California's mountains. Fire spread in chaparral fuels has been described as a crown fire as well as a surface fire with a deep fuel bed. In varying degree, physical characteristics of fuels and fuel beds, such as fuel moisture content, fuel loading, fuel surface area-to-volume ratio and fuel bed porosity, influence ease of ignition, rate of spread, burning time and fire intensity. How these variations affect fire behavior is only known in a general way. However few explicit relationships have been established, particularly for the combinations of these factors as they appear naturally in chaparral fuel beds. For the purpose of studying wildfire spread in natural chaparral fuel beds, this paper focuses on an experimental investigation of laboratory-scale flame plume proprieties of live shrub fuels. Here a fire starts in a circular shrub fuel bed in still air (Fig. 3). The solid surface of shrub fuel is heated, by radiation and convection from the burning products, and pyrolyzes to form vapor-phase fuel. Combustion of the pyrolyzate forms a flame plume above the fuel bed that is made visible by radiation from soot particles generated by the diffusion flame. Ambient air is entrained from the environment into the fire plume to oxidize the pyrolyzate fuel. Because the momentum flux of the pyrolyzate is very small, buoyancy forces control the fire plume. As heat transfers from the fire plume to the fuel bed, the fire spreads across the fuel bed. The geometry of the fire plume, especially its height, is one of the important parameters that determine the radiation flux from the fire. Albini (1981) suggested that flame height corresponded to the height at which 10 times the

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stoichiometric air requirement is incorporated into the flow.

Fig.1. Chaparral is a mixture of several different species of shrubs that grows in the Mediterranean climate of California

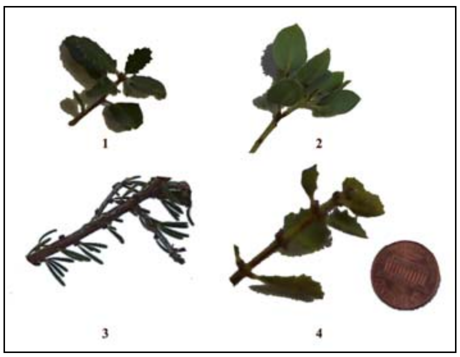

Fig. 2. Shrub oak (1), Manzanita (2), Chamise (3) and Ceanothus (4). A one cent coin is used to show the size.

Fig. 3. Fire plume of live chamise shrub fuel. The experimental set up including fuel container, thermal insulation barrier and digital weight scale is illustrated.

Since the total energy lost by radiation from the flame ranges from 30% for a methane flame up to 45% for sootier flames, this flux can be a very important component in a fire model and can strongly influence the rate of spread of fires (1995). Albini (1986 and 1996) developed a wildland fire spread model, in which radiation is considered as the dominant mechanism of energy transfer to the fuel in front of the burning zone. The radiant flux from the flame depends strongly on the mass fraction, geometric distribution and temperature of the soot in flaming region. Thus the geometry of the fire plume as well as the fuel properties have a strong influence on the heat-release rate and the rate of fire spread.

Some fire plume phenomena are understood well enough that simple algebraic representations can be given. These include fire height measured by Thomas (1963) who used wood cribs, You and Faeth (1979) who used wicks with a range of alcohol fuels, McCaffrey (1979) who used natural gas flames on 0.30 m square burners, and Cetegen (1982) who used simple gaseous fuels such as methane, natural gas and propane on circular burners. Other work investigating the effect of wind velocity on flame length includes Scesa (1957), Thomas (1963), Putnam (1965), Albini (1981), Nelson and Adkins (1986), and Weise and Biging (1996). Many of these authors have confirmed the dependence of flame length and tilt on the Froude number.

However, there is no information currently available to describe the fire plume above live shrub fuels. While one would hope that models based on combustion of dead fuels and natural gas would be applicable to living plant fuels, this has not been confirmed widely. Details of the combustion processes unique to living vegetation are unknown and may explain the dynamic fire behavior observed in these fuels. Given the complexity of fire plumes of shrub fuel, which involves turbulent flow, chemical reactions and varied characteristics of fuel and fuel bed, it is not surprising that very little information on fire plume properties currently exists. The overall objective of this paper was to examine the effects of fuel bed diameter and porosity on properties of the fire plume—specifically on estimated velocities and temperatures within the flame zone. This was accomplished by experimentally measuring and comparing the mass loss rate, mean flame height, temperature structure and velocity field of shrub fire plume under varied conditions.

2. EXPERIMENTAL DETAILS

2.1 Fuel Collection

In the present experiment, the shrub fuels analyzed were collected from an experimental area 50km east of Riverside, California between October and December 2002. Plants were still dormant and very dry following the dry summer season because no precipitation had occurred to stimulate growth. Active wildfires typically occur during this period of time. Branches and foliage of shrub fuels with diameter up to 6.3 mm were used (see Fig.2). Foliage was retained on the branches. Branches were cut from living plants in the morning of the experiment so as to minimize moisture loss through transpiration. Dead fuel was removed to the extent possible. The shrub fuels were then bagged and transported to the burn facility at the USDA Forest Service Forest Fire Lab Laboratory in Riverside, California. Fuel moisture content (oven-dry basis) was determined using a Computrac* moisture analyzer immediately prior to burning. Fuel particle density was determined by water displacement.

2.2 Experimental Setup

Fuel beds were constructed by placing a fixed mass of a selected species in a circular screen container of known diameter (Fig. 3). The fuel was spread uniformly in the container, fluffed to remove tightly packed concentrations, and lightly and uniformly pressed down to the final fuel bed depth. Extraneous vertical strands above the bed surface were then clipped. A paper towel saturated with a known mass of denatured alcohol was placed below the screen container. The entire assembly rests on an electronic scale (8 kg maximum loading, 0.1 g resolution). The electronic scale is connected to a computer data acquisition system via an RS-232 port and Labview (National Instruments Co.) software. A CANNON-ZR40 digital video camcorder was used to record the flame geometry at a framing rate of 30 frames s^{-1}. The temperature structure of the fire plume was measured by a FLIR ThermaCAM™ SC500 IR-camera.

2.3 Statistical Design

One purpose of this experiment is to investigate the effects of fuel bed diameter on fire plume properties of burning live shrub fuels. Fuel bed diameters of 30, 45 and 60 cm were tested. The fuel bed depth δ is a constant equal to the height of the container (20 cm). The packing ratio is defined as

$$\beta = \frac{W}{(M+1)A\delta\rho_p}, \qquad (1)$$

where W is the total fuel bed mass at time t =0, M is the moisture content expressed as a proportion, A is fuel bed surface area, δ is fuel bed depth, and ρ_p is fuel particle density (Rothermel 1972). Even though the packing ratio was held constant; this value is still larger than that calculated from the wildland fuel where the fuel bed volume is obtained by assuming the stand shrub occupies a cylinder having the height of the shrub and a diameter equal to the average crown diameter (see Fig. 1).Since the fuels were collected from plants, fuel properties are somewhat variable in comparison to milled fuels such as dowels and matchsticks. Four dominant chaparral species were selected for burning: manzanita, hoaryleaf ceanothus, chamise, and scrub oak. Each fuel bed was composed of a single species. Three replications of each diameter for each species were burned yielding a total of 36 experimental burns.

2.4 Data Collection

Mass loss $W(t)$ was determined by recording the sample mass at 1 Hz using the electronic scale and then calculating the mass loss rate, dW/dt. Flame height was determined from measurements made from video recordings and very short time exposure photographs. A selected sequence corresponding to one hundred consecutive frames of each test was then analyzed in the computer. Video pictures capture the visible light from the flame itself and record the radiation emitted by burning soot particles. It is expected that the radiation from soot is approximately indicative of the regions of intense chemical reaction.

Because the wavelengths of thermal emissions are in the IR range between 3 and 15 μm, and thermal emission is proportional to the fourth power of surface temperature, IR cameras have been used successfully to detect and map temperature field within wildfires. Successive images captured from IR camera can provide a non-contact estimate of the temperature field. The minimum accuracy of the estimates for the temperature range used in this experiment was ±30°C. The maximum image sampling rate of the thermal camera (60 Hz) was used. ThermaCAM™ 2000 software was used to obtain 320×240 pixel temperature field, which can be validated by using 24 gauge chromel-alumel (Type K) thermocouples measuring known temperature field before the experiment. The thermocouples can also be used at the separate points above the fuel field to estimate the emissivity for the various flames that we are studying.

3. RESULTS AND DISCUSSION

A total of 36 experimental fires were burned between October and December, 2002 (Fig. 3). Mean live fuel moisture content of foliage and branches < 6.3 mm diameter was 57, 70, 60, and 60% for chamise, ceanothus, manzanita, and scrub oak, respectively.

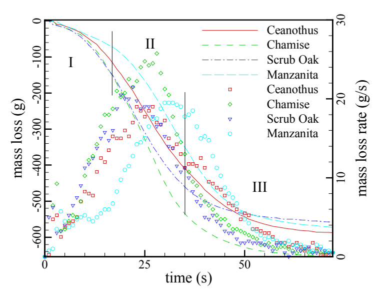

Fig. 4. Mass loss (lines) and mass loss rate (symbols) of four shrub fuels with time for burner diameter 45 cm.

3.1 Mass Loss Rate of Four Shrub Fuels

Due to natural fuel bed variability and entrainment of environmental air, the bottom of the fuel bed could not be ignited uniformly. As seen in Fig. 3, the fire starts generally from the center and then spreads to the boundary. This is different from liquid pool fire, which can be ignited uniformly and the total burner surface is covered by fire at the same time. After ignition of the fuel bed, the overall burning rate reached a maximum value in a short time. This is illustrated in Fig. 4 by plotting the mass loss rate of these four shrub fuel bed for burner diameter 45 cm. The burning rate of the shrub fuel can be measured by the mass loss rate. As seen

* The use of trade names is provided for information only and does not constitute endorsement by the U.S. Department of Agriculture.

from Fig. 4, three combustion phases can be defined roughly. The first phase I, corresponding to early time (0 to 15 s), includes the combustion of the igniting source. We assumed that this phase also includes the vaporization of water from the foliage and surface layers of branches. A large amount of white smoke is visible during this phase. The mass loss rate is relatively small. In the second phase II (15 to 35 s), the mass loss rate attains a maximum and remains steady for a period. Biswell (1974) noted that chamise is generally considered to be highly flammable than other chaparral species, while ceanothus resists fire well when young. Comparing the maximum mass loss rate of these four shrub fuels, we find the mass loss rate of chamise is highest, that of shrub oak is higher than that of manzanita, while that of ceanothus is lowest. The result is consistent with Biswell's observations. During the period of steady burning it is mainly the gas combustion of pyrolysate from the heated solid surface of shrub fuels. Little carbon is burned (Zukoski 1995). Under the control of buoyancy forces, combustion of the pyrolysate forms a fire plume above the fuel bed. At the region above the top of the flame, black smoke with flash soot is visible. In this paper, the reported fire plume properties such as flame height are averaged over this steady burning period. After the burning of volatile gas, the final burning phase III is the combustion of carbonaceous residue at a reduced burning rate. The mass loss rate decreases slowly and finally reaches zero. The combustion process is thus completed.

3.2 Flame Height of Four Shrub Fuels

The presence of strong periodic pulsations in the flame height is a common feature of fire plumes. It also can be observed over shrub fire plume. The flames are characterized by a strong columnar fire plume with a diameter close to that of the burning area of the fire (Fig. 3). The instantaneous flame height over 100 successive flame images or a time period of 3.3 s was used to calculate mean flame height for four shrub fuels and three different burner diameters respectively (Fig. 5). The flame heights of four shrub fuels are different and increase with diameter. This is because the flame height depends strongly on the heat-release rate of the fire and the burner diameter (Zukoski 1995). The heat-release rate is simply defined as

$$\dot{Q}_f = -h(dW/dt) \tag{2}$$

where h is the heating value of shrub fuel (ASTM 1966). The mass loss rate, dW/dt, was calculated as a mean value of burning rate reached maximum and remained steady for a period (Fig. 4, phase II).

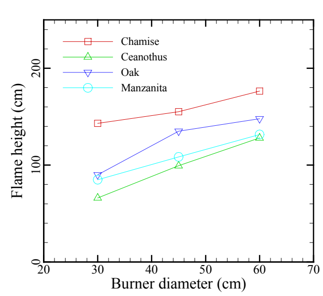

Fig. 5 Mean flame height plotted versus burner diameters for four shrub fuels.

For the study of fire plume, a usual engineering technique is to use similarity parameters to carry out experiments and apply the results to other configurations of the system. In this paper a dimensionless heat-release rate term Q^* is defined as

$$Q^* = \frac{\dot{Q}_f}{\rho_\infty T_\infty c_{p\infty}\sqrt{g\mathrm{D}}\mathrm{D}^2} \tag{3}$$

where $c_{p\infty}$, T_∞ and ρ_∞ are specific heat, temperature and density of ambient air, g is the acceleration due to gravity, and D is the burner diameter. The results of Zukoski (1995) suggest that Q^* may be one of the most important parameters in controlling the geometry of fire plumes. The dimensionless flame height is scaled as Z_{fl}/D. For three diameters and four species, the flame heights are shown in Fig. 6 in the form of a scatter plot of Z_{fl}/D versus Q^*. The value of Z_{fl}/D increases with Q^*. For comparison, the dimensionless result of Zukoski (1995) obtained for gas fuels is also plotted in Fig. 6 as a solid line. The flame height for shrub fuel is lower than that of Zukoski (1995) for gas fuels. This is mostly due to the nonuniformity of shrub fuel in ignition and combustion process. From the data presented in Fig. 6, an explicit relationship can be established to describe the dependence of flame height on burner diameter and heat release rate in the fire as:

$$\frac{Z_{fl}}{D} = 2.27 Q^{*2/5} \tag{4}$$

Because it describes a line with a slope of roughly 2/5, the diameter effect can be eliminated completely since

$$\frac{Z_{fl}}{D} \propto \left(\frac{\dot{Q}_f}{D^{5/2}}\right)^{2/5} \propto \frac{\dot{Q}_f^{\,2/5}}{D} \tag{5}$$

If the parameters of environmental air are assumed as constant, thus Eq. (4) can be expressed as:

$$\frac{Z_{fl}}{\dot{Q}_f^{\,2/5}} \approx 0.137 \tag{6}$$

that means the flame height, Z_{fl}, mainly depends on the heat release rate, $\dot{Q}_f$, in the fire.

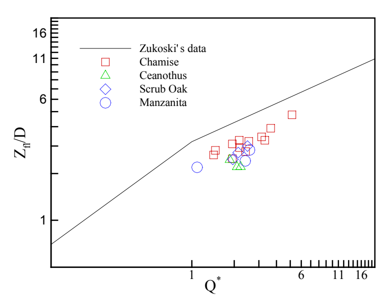

Fig. 6. Normalized flame heights of four shrub fuels are scattered versus normalized flame heat release rate. The result of Zukoski (1995) is also illustrated as a solid line.

3.3 Temperature Structure

A thermal infrared camera was used to capture the instantaneous temperature images of fire plume of shrub fuel at a sampling rate of 60 Hz. It is noted that each IR temperature image represents an average over a significant depth into the flame front, so the highly resolved successive temperature fields obtained from the present IR camera can help us analyze the internal properties such as fuel combustion and radiative heat transfer of fire plume. For burner diameter 45 cm, Fig. 6 illustrates an instantaneous and a time-averaged temperature field over a time period of 2.0 s or 120 successive temperature images of chamise fuel. The temperature images were taken with the IR camera located 5.0 meters away from the burner and the field of view extends from the top of the burner to the edge of the turbulent fire plume. The instantaneous temperatures have large fluctuations over the time-averaged values. Fig. 8 shows the instantaneous and time-averaged temperature profiles of chamise at vertical height of 1.39 m above the surface of the burner. Time-averaged temperatures do have a radial variation that is nearly Gaussian. However, instantaneous temperature profiles are more nearly top hat in shape. The profiles have much steeper sides and more nearly constant values across the instantaneous center of the plume. The time-averaged temperature Gaussian shape results in part because the instantaneous center of the top hat profile wanders about the centerline defined for the time-averaged plume. Assuming Gaussian profile for time-averaged temperature difference, $\Delta T = T(r,z) - T_\infty$, in the radial direction, r, the normalized temperature can be expressed as

$$\frac{T(r,z) - T_\infty}{T_m(z) - T_\infty} = \exp\left[-\beta (r/R_t)^2\right] \tag{7}$$

where $T(r,z)$ is the time-averaged temperature at radial location and height, $T_m(z)$ is the maximum temperature at height, and T_∞ is the environmental temperature. The quantity R_t represents the width of the temperature profiles corresponding to the radial location of

$$T(r,z) - T_\infty = 0.1\left[T_m(z) - T_\infty\right]. \tag{8}$$

The variable β is a constant that can be estimated from temperature profiles. Here $\beta \approx 1.15$ for these data.

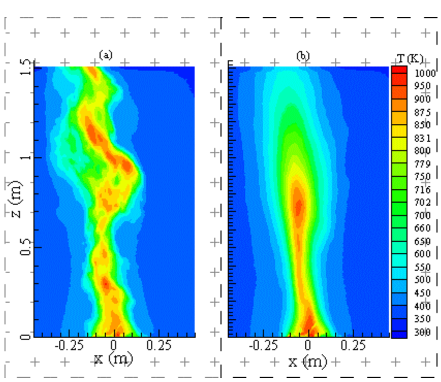

Fig. 7. Instantaneous (a) and time-averaged (b) flame temperature field of chamise obtained from IR thermal camera

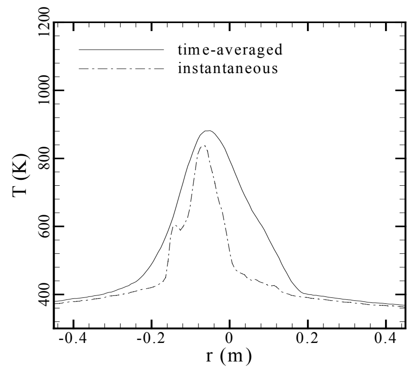

Fig. 8. Time-averaged and instantaneous flame temperature profiles of chamise versus horizontal radial locations.

4. CONCLUSIONS

Chamise (*Adenostoma fasciculatum*), manzanita (*Arctostaphylos densiflora*), scrub oak (*Quercus berberidifolia*) and hoaryleaf ceanothus (*Ceanothus crassifolius*) are the most hazardous brush fuels that grow in the mountains of southern California and throughout the Coast Ranges. This paper focuses on a comparison of overall burning characteristics of these four shrub fuels by investigating the mass loss rate, flame geometry and temperature structure of chaparral fire plume. The higher mass loss rate results confirm observations that chamise is the most flammable of the four species examined. With similar fuel moisture content, ceanothus was the least flammable of the four species which was reflected in the lowest mass loss rate. The reasons for these differences are due to different physical and perhaps chemical characteristics of these fuels. It was observed that flame height increases mainly with heat release rate. Using dimensionless parameters, simple explicit relationships were established to describe the temperature profile of live chaparral fire plume.

5. ACKNOWLEDGEMENTS

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