

AN INVESTIGATION OF CROWN FUEL BULK DENSITY EFFECTS ON THE DYNAMICS OF CROWN FIRE INITIATION IN SHRUBLANDS¹

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*Crown fire initiation is studied by using a simple experimental and detailed physical modeling based on Large Eddy Simulation (LES). Experiments conducted thus far reveal that crown fuel ignition via surface fire occurs when the crown base is within the continuous flame region and does not occur when the crown base is located in the hot plume gas region of the surface fire. Accordingly, the focus in this article is on crown fuel ignition when the crown base is situated within the intermittent flame region. In this region, the flame shape and height changes with time over the course of pulsation. This causes the flame to impinge on the crown fuel base and the hot gas is forced through the crown fuel matrix. Under certain conditions, it is observed that the crown fuel bulk density affects the impingement of flame and the ignition of crown fire. The crown fuel properties used were estimated for live chamise (*Adenostoma fasciculatum*) with a fuel moisture content of 44% (dry basis). As the crown fuel bulk density is increased from $0.75 \text{ kg} \cdot \text{m}^{-3}$ to $1.75 \text{ kg} \cdot \text{m}^{-3}$, it is observed that the average hot gas velocity inside the crown matrix decreases from $0.70 \text{ m} \cdot \text{s}^{-1}$ to $0.52 \text{ m} \cdot \text{s}^{-1}$, thus, resulting in less entrained air passing through the crown fuel and more energy accumulation inside the crown fuel matrix. Higher bulk density also influences the surface fire. As the hot gas flows into the crown fuel matrix is retarded, the average hot gas temperature at the crown fuel base increases from 768 K to 1,205 K. This is because the mixing rate of air and combustible gas around the base of crown fuel increases. Although higher fuel bulk density means more fuel must be heated, the increase in accumulated energy per unit volume within the crown fuel matrix is higher than the additional heat needed by the fuel. Thus, the average crown fuel temperature increases and ignition occurs at higher bulk density.*

Keywords: Crown fire; LES; Transition

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INTRODUCTION

Wildfires occur in forests and shrublands throughout the world and spread in the elevated living foliage and branches of these vegetation types. These crown fires occur in shrub fuel types called chaparral (California), matorral (Chile, Argentina), fynbos (South Africa), garrigue and maquis (Mediterranean), and mallee-heath (western Australia) to name a few. The ability to predict shrub canopy ignition, leading to a high-intensity fire spread, is necessary to manage fire risk in these areas. Current operational crown fire models are primarily designed for ignition of tree canopies in coniferous forests (e.g., douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), black spruce (*Picea mariana*) in which the canopy height, crown base height and canopy bulk density are significantly different from shrub canopy).

The canopy height refers to the highest height at which the canopy fuel density exceeds $0.011 \text{ kg} \cdot \text{m}^{-3}$, and crown base height refers to the vertical distance between the surface fuel and the lowest height at which the canopy fuel density exceeds $0.011 \text{ kg} \cdot \text{m}^{-3}$ (Andersen et al., 2005; Scott and Reinhardt, 2001). In this study, the crown fuel bulk density refers to the oven dry mass of foliage and small twigs (less than 3 mm in diameter) per unit volume of canopy (Alexander, 1988; Finney, 1998; Keane et al., 2005; Van Wagner, 1977) and the gross crown fuel bulk density is defined as the total oven dry mass of crown fuel (including foliage, small twigs and branches) per unit volume of canopy. In the case of conifer forests, canopy heights range from 5.00 m to 50.00 m, canopy base height ranges from 0.30 m to 35.00 m, and typical canopy bulk densities are in the range of $0.09 \text{ kg} \cdot \text{m}^{-3}$ to $0.96 \text{ kg} \cdot \text{m}^{-3}$ (Alexander and Cruz, 2006; Andersen et al., 2005; Cruz et al., 2003; Keane et al., 2005). The corresponding values in the case of chaparral shrub canopies are 1.00 m to 3.00 m for shrub canopy height (Hanes, 1971), estimated 0.60 m to 1.00 m for canopy base height, and $0.20\text{--}2.10 \text{ kg} \cdot \text{m}^{-3}$ for bulk densities (Countryman and Philpot, 1970).

Currently, many semi-empirical models are available for fire management systems in conifer forest (see Alexander, 1998; Cruz et al., 2004; Cruz et al., 2006; Plucinski, 2003; Scott and Reinhardt, 2001; Van Wagner, 1977; Xanthopoulos, 1990). Van Wagner (Van Wagner, 1977) developed a simple semi empirical model utilizing plume theory to predict the minimum surface fire intensity to initiate crown fire. To improve prediction accuracy, additional factors that affect crown fire initiation such as wind, flaming residence time, and surface/crown fuel characteristics, etc., were included. Recently, a semi-empirical model based on heat transfer theory was developed by Cruz et al. (Cruz et al., 2006a; Cruz et al., 2006b) to obtain a better explanation of the crown fire initiation. Energy balance was used to predict the temperature of crown fuel. Ignition was successful if the simulated temperature of crown fuel exceeded ignition temperature of 600 K.

Since convective heat transfer is an important mechanism controlling crown fire initiation (Butler et al., 2004a), its prediction was highly dependent upon crown fuel characteristics that affect convection directly (Cruz et al., 2003). Differences in crown fuel characteristics generally lead to a difference in the unsteady interaction between the surface fire and crown fuel. In conifer forests, the important factors used to predict the ignition of crown fuel, are canopy base height, canopy

bulk density, and foliar moisture content (Albini, 1996; Alexander, 1988, 1998; Cruz et al., 2004; Scott and Reinhardt, 2001; Van Wagner, 1977). For shrub canopies, the canopy base height is assumed not to be an important factor since the variation in canopy base height in a shrub canopy is much smaller than that for a conifer forest.

The crown fuel bulk density is thus considered to be a significant factor because of the difference in the values of canopy bulk density between shrub canopies and conifer canopies. Therefore, in the present paper, crown fire initiation was studied by using laboratory experiments and detailed physical modeling based on a three-dimensional large eddy simulation (3D LES). The model was used to highlight and quantify the physical processes involved in the dynamics of shrub canopy ignition. Both the experiments and the model were specifically designed to better understand the impact of variation of the crown fuel bulk density on crown fire initiation by a surface fire.

DESCRIPTION OF EXPERIMENTAL SETUP

In vegetation complexes subject to crown fire, there tends to be a non-uniform distribution of underbrush fuel between surface and crown fuels. To simplify, we assumed no vertical continuity in fuels ("fuel ladder") and experimentally modelled a gap between surface and crown fuels as Albini (Albini, 1996) did. Thus, the crown base height (Z_{cb}) was the lowest height above the ground at which there was sufficient canopy fuel to propagate fire vertically through the canopy as defined by Van Wagner (Van Wagner, 1993). The experimental set up is shown in Figure 1a. A mass of 0.45 kg of aspen (*Populus tremuloides*) excelsior, evenly distributed over a 0.80 m $\times$ 1.80 m flat bed, was used to represent the surface fuel as shown in Figure 1b.

A surface fuel bed depth of 0.10 m was chosen so that the resulting flame height ranged from 0.15 m to 0.45 m. This was deemed adequate and safe for indoor experiments. The surface fuel was ignited along a line parallel to its width of 0.80 m. The crown fuel was comprised of live chamise (*Adenostoma fasciculatum*) with foliage diameter of ≈ 0.50 mm and branch diameter of approximately ≈ 3.50 mm. The crown fuel bulk density used in this study was higher than that in the field. This is because the bulk density data currently available is based on the average value over the whole canopy volume. However, the distribution of chaparral fuels in the field is typically non-uniform. The live foliage and fine fuels (with diameters less than 3.50 mm) of chaparral in the field are mostly present in the middle portion of canopy (Weise unpublished data). This causes the bulk density in this portion to be higher than the average value of bulk density. It was estimated to be 1.41 times higher than that of the average value. Thus, the crown fuel bulk density in this portion could be in the range from $0.28 \text{ kg} \cdot \text{m}^{-3}$ to $2.96 \text{ kg} \cdot \text{m}^{-3}$. Accordingly, three crown fuel bulk densities of 0.75, 1.75, and $2.75 \text{ kg} \cdot \text{m}^{-3}$ were considered for a detailed investigation in this study. The mass proportions of foliage and branch were approximately 53% and 47%, respectively. Thus, the gross crown fuel bulk densities were 1.40, 3.30, and $5.20 \text{ kg} \cdot \text{m}^{-3}$, respectively, for the selected crown fuel bulk densities.

All chamise samples were approximately the same size, and were collected from the same field location in Riverside County, California. The crown fuel was arranged

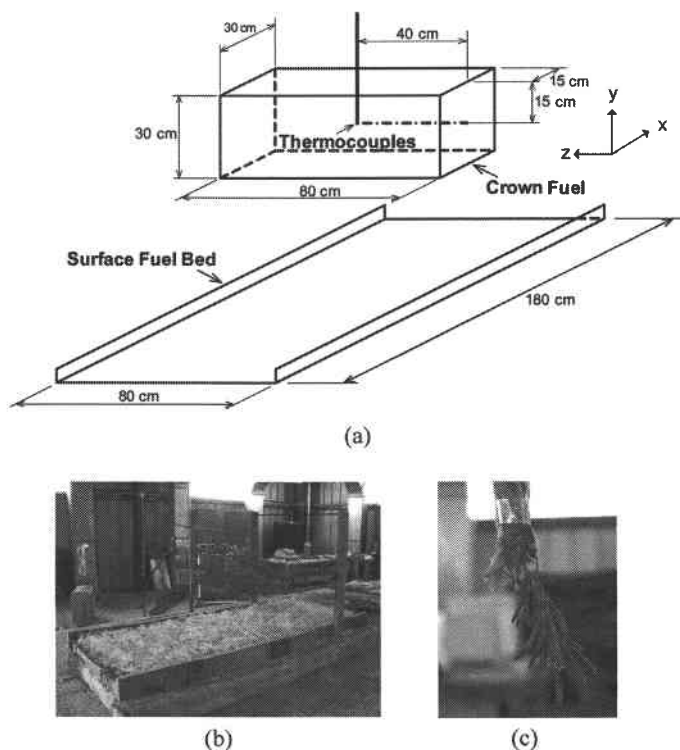


Figure 1 Illustration of (a) the experimental setup, (b) the surface and crown fuel, and (c) the thermocouple utilized for temperature measurements.

in a volume with dimensions $0.30 \text{ m} \times 0.30 \text{ m} \times 0.80 \text{ m}$ in height, depth and width. These dimensions were chosen initially because it was found to be adequate for crown fuel to ignite under the experimental conditions. The crown fuel was placed on a coarse wire mesh with 2.54 cm hex size ($\sim 1 \times 1$ mesh per inch). The mesh diameter is 0.9 mm and thus the percentage of open area is 85%. This ensured that the hot gas flow, originating from the surface fire, was essentially unimpeded except for the presence of the crown fuel. The dry-basis moisture content of chamise (both the foliage and the branch) is in the range of 42.70–45.50% (for all experiments). It was measured using an Arizona Instruments Computrac² moisture analyzer a few minutes prior to the experiment. The temperatures of the crown fuel and hot air from the surface fire were recorded at every 1.0 seconds by a set of 30 gauge (0.25 mm diameter) type K (chromel-alumel) thermocouples with a response time of 0.3 s. One of the thermocouples was inserted into a 2.0 mm diameter branch of chamise so that the measured temperature approximates the crown fuel temperature as

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shown in Figure 1c. The thermocouples were located at the middle of the crown fuel bed as can be seen in Figure 1a. The gap between each thermocouple was less than 2.0 cm. Radiation correction was applied (Cox and Chitty, 1985) and the temperature was corrected approximately 63 K for a thermocouple reading of 900 K.

A Canon-ZR40 digital video camera, which is capable of taking 30 frames per second, was used to record the experiment. This camera was adequate to measure the rate of spread of surface fire and the unsteadiness of the flame. The flame pulsation frequency f could be estimated based on the wavelength of a gravity wave as $f = \sqrt{g/2\pi\lambda}$ in which the wavelength λ is correlated with the burner diameter (Thuillard, 2002). For a rectangular burner, in which w is the width of the shorter side, Thuillard (2002) found that λ has an empirical relation with burner width (m), yielding $f = \alpha/\sqrt{w}$ where α is a correlation constant with a value of $1.25 \text{ (m}^{1/2} \cdot \text{s}^{-1}\text{)}$.

By assuming that the line fire in the present work had a rectangular base in which the width was the shorter side, the pulsation frequency was estimated to be 4.7 Hz for a visible base width of 7.0 cm estimated from the experiments. This estimate agrees reasonably well with the experimentally observed pulsation frequency of 5.1 Hz. The observed pulsation frequency was obtained by first calculating the average visible flame height over 30 consecutive frames or a time interval of 1 second. Then, the frequency is equal to the number of observed cycles of the flame height crossing the average. The crown fuel base height was set to be 0.20 m above the surface fuel. Each experiment was repeated three times for the same nominal values of the controlling variables to eliminate effects of small changes in experimental conditions.

MODEL DESCRIPTION

A detailed physics-based simulation of hot gas flow within crown fuel to determine fire-fuel interaction is expensive and requires extensive computation. This is because the spectrum of the relevant length scales is large and it is necessary to achieve accurate results for all these scales. Thus, Large Eddy Simulation (LES) is a good candidate to simulate crown fire initiation. The basic idea in LES is to resolve the large scales accurately and model the effects of small scales represented as Sub Grid Scale (SGS) terms to include the effect of the unresolved scales on the resolved ones. In LES, the instantaneous, time-dependent, three-dimensional governing transport equations for various field quantities are spatially filtered (Rogallo and Moin, 1984). This results in a set of governing equations for the gas phase which include the resolved field (large scale) and sub grid scale terms representing processes occurring at scales smaller than the filter size (Zhou et al., 2006):

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i}{\partial x_i} = \bar{S}_{s-g} \quad (1)$$

$$\frac{\partial \bar{\rho} \tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_j \tilde{u}_i}{\partial x_j} = \frac{\partial}{\partial x_j} \{ -\bar{\rho} (\widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j) \} - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \bar{\tau}_{ij}}{\partial x_j} + \bar{\rho} g_i - \bar{F}_{s,i} \quad (2)$$

$$\frac{\partial \bar{\rho} \tilde{h}}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_j \tilde{h}}{\partial x_j} = \frac{\partial}{\partial x_j} \{ -\bar{\rho} (\tilde{u}_j \tilde{h} - \tilde{u}_j \tilde{h}) \} - \frac{\partial \bar{q}_i}{\partial x_i} - \bar{q}_{conv} - \bar{q}_{rad} + (1 - X_c) \bar{m}_{s,char} L^{char} \quad (3)$$

$$\frac{\partial \bar{\rho} \tilde{Y}_K}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_j \tilde{Y}_K}{\partial x_j} = \frac{\partial}{\partial x_j} \{ -\bar{\rho} (\tilde{u}_j \tilde{Y}_K - \tilde{u}_j \tilde{Y}_K) \} + \frac{\partial \bar{q}_{Y_K,i}}{\partial x_i} + \bar{S}_{s-g,K} + \bar{\omega}_K \quad (4)$$

where $\bar{\rho}$ is the filtered gas mixture density, $\tilde{u}_i$ denotes the Favre-filtered velocity component along x_i , t is time, $\bar{S}_{s-g}$ is the filtered mass production rate, and $\bar{F}_{s,i}$ is the filtered i -th component of the drag force resulting from the interaction between the gas and solid phase; it is non zero only within the fuel layer.

It is approximated as $F_{s,i} = 0.5 C_D \bar{\rho} |u| \tilde{u}_i$ where the drag coefficient is given by $C_D = 24(1 + 0.15 \text{Re}^{0.687})/\text{Re}$ where Re is the Reynolds number defined in terms of fuel particle diameter, fluid density, fluid velocity, and dynamic fluid viscosity (Zhou et al., 2005). The variable $\bar{p}$ denotes filtered pressure, g_i is the body force per unit mass vector, and $\tilde{h}$ is the gas mixture enthalpy. The quantity $\bar{q}_i$ represents the filtered heat flux vector, $\bar{q}_{conv}$ and $\bar{q}_{rad}$ denote the convective and radiative heat transfer rates per unit volume between the solid and gaseous phase respectively, L^{char} denotes the specific enthalpy associated with char combustion, and $\tilde{Y}_K$ is Favre-filtered mass fraction. The filtered reaction rate $\bar{\omega}_K$ of species K is estimated as the product of the consumption rate per unit surface area and the filtered flame surface density (FSD) (Zhou and Mahalingam, 2002). Other methods to simplify treatment of gas phase combustion exist, see for example Mell et al. (2007). The first terms on the right-hand side in Eqs. (2), (3), and (4) are the unresolved SGS convective fluxes of momentum, energy, and species; they are modeled using a gradient approximation model after Smagorinsky (Bardina et al., 1983).

For the solid phase, the crown fuel was modelled as a porous medium where the solid phase is comprised of two categories: foliage and branches. Initially, the solid phase is assumed to contain water, pyrolyzates, char, and non combustible ash. The temperature of the solid phase increases when it absorbs radiative and convective heat transfer from the gas phase. The incoming heat will contribute to the vaporization of water and the decomposition of cellulose (foliage) and wood into combustible gases. Subsequently, the crown fuel may end up igniting when its temperature reaches an appropriate ignition temperature. The mass and energy equations for the solid phase is given by (Zhou et al., 2006).

$$\frac{\partial \bar{m}_s}{\partial t} = -\bar{m}_{s,H_2O} - \bar{m}_{s,pyr} - \bar{m}_{s,char} \quad (5)$$

$$\frac{\partial \bar{c}_{p,s} \bar{m}_s \bar{T}_s}{\partial t} = \bar{q}_{conv} + \bar{q}_{rad} + \bar{q}_{mass} \quad (6)$$

where $\bar{m}_s$ is the mass of the solid phase and $\bar{m}_s$ terms in Eq. (5) with appropriate subscripts denote the rates of solid mass reduction due to drying, pyrolysis, and char oxidation.

The variables $\bar{q}_{conv}$ and $\bar{q}_{rad}$ are convective and radiative heat exchange terms that appear in Eq. (3) as well. The quantity $\bar{c}_{p,s}$ is the filtered specific heat of the solid fuel and $\bar{q}_{mass}$ is the rate of heat loss/absorption due to water vaporization, pyrolysis, and char oxidation. Submodels for these quantities are described elsewhere (Zhou et al., 2005). The generic governing equations of gas phase were discretized in a three dimensional (3D) Cartesian coordinate system and numerically integrated by the QUICKEST scheme (Leonard, 1979). Pressure-velocity coupling was treated using the SIMPLER method (Patankar, 1980). Radiative heat transfer from soot particles produced in the flame and from the burning of solid fuel to gas/solid phases inside a porous medium was calculated by a 3D Discrete Ordinates (DO) method (Modest, 1993).

A surface fuel bed size of 1.20 m long and 0.80 m wide was used. The surface fuel properties used were that for aspen (*Populus tremuloides*) excelsior with fuel particle diameter of 1.0 mm. The bulk density, depth of the surface fuel, fuel particle density, surface area-to-volume ratio, moisture content, heat of char combustion, char content, and ash content were $3.13 \text{ kg} \cdot \text{m}^{-3}$, 0.10 m, $400 \text{ kg} \cdot \text{m}^{-3}$, $4,000 \text{ m}^{-1}$, 7%, $32.37 \text{ MJ} \cdot \text{kg}^{-1}$, 15.4%, and 0.35%, respectively (Susott, 1982). The crown fuel properties used were that for live chamise (*Adenostoma fasciculatum*) with foliage diameter of 0.5 mm and branch diameter of 3.5 mm. The proportions of foliage and branch were 53% and 47%.

The physical properties of foliage were $500 \text{ kg} \cdot \text{m}^{-3}$, $8,000 \text{ m}^{-1}$, 42%, $31.35 \text{ MJ} \cdot \text{kg}^{-1}$, 28.60%, and 3.50%, respectively, for the fuel particle density, surface area-to-volume ratio, moisture content, heat of char combustion, char content, and ash content. The corresponding properties for the branch phase were $600 \text{ kg} \cdot \text{m}^{-3}$, $1,143 \text{ m}^{-1}$, 35%, $31.35 \text{ MJ} \cdot \text{kg}^{-1}$, 14.30%, and 0.50% respectively, (Ragland et al., 1991; Susott, 1982). The overall dimensions of the crown fuel were 0.30 m long, 0.30 m high and 0.80 m wide with a base height of 0.20 m above surface fuel. The branches were assumed to have the same kinetic parameters as wood (Ragland et al., 1991). The kinetic parameters for the pyrolysis rate of leaves were modeled using the model of Porterie et al. (Porterie et al., 2000) for pine needles (Zhou et al., 2005) since the difference in the type of species of leaves has only a small affect on the pyrolysis behavior (Smith et al., 2004; Susott, 1982). However, this issue needs further investigation.

Since the composition of the pyrolysis gas is complicated, the pyrolysis gas was assumed to be CO for simplicity and only five chemical species (i.e., CO, CO₂, H₂O, O₂, and N₂) were used to describe fuel gas, air, and products of combustion. A 3D computational domain 1.20 m long, 1.20 m high and 1.20 m wide was designed. All boundaries except the bottom are open boundaries in which all values at the boundaries have zero gradient conditions. A uniform grid system of 340,628 cells ($82 \times 67 \times 62$ cells) was used to span the computational domain. Grid independence was tested by increasing the number of grid cells to 727,668 ($102 \times 87 \times 82$ cells) while maintaining the same Courant number of 0.10. When considering the profile of hot gas temperature, velocity, and solid phase temperature, it was found that both the high and low resolution grids captured the same trend. Since the ignition of the crown fuel is driven by the solid phase temperature, we focused attention on this quantity in comparing results from the low and high resolution simulations. Since differences in the solid phase temperatures were less than 10%, it was deemed that the lower resolution results are sufficient for the purpose of investigating the ignition process.

RESULTS AND DISCUSSION

Experimental Results

The effect of varying crown fuel bulk density was investigated experimentally. In the experiment, the surface fire spread at an average rate of approximately $1.1 \text{ cm} \cdot \text{s}^{-1}$, with a standard deviation of $0.1 \text{ cm} \cdot \text{s}^{-1}$. It was approximated from the distance over which the fire front propagates divided by the corresponding time difference. The average visible flame height was 0.32 m with a standard deviation of 0.02 m. The minimum and maximum flame heights were 0.15 m and 0.45 m, respectively. Thus, the continuous flame region was the height between 0.00 m and 0.15 m and the intermittent flame region was the height between 0.15 m and 0.45 m. The crown base ($Z_{cb} = 0.20 \text{ m}$) was thus located in the intermittent flame region of the surface fire as shown in Figure 2.

Figure 3 shows time evolution of experimental air (T_a) and solid phase (T_s) temperature of the branch inside crown fuel for three crown fuel bulk densities. When the flame impinged on the crown fuel base with the crown fuel bulk density of $0.75 \text{ kg} \cdot \text{m}^{-3}$, it was observed that the hot gas flows easily through the crown fuel. This is apparent from the shape of the surface fire evident in Figure 4a. The temperature of hot combustion products originating from the surface fire decayed to 581 K (were shown to be repeatable to $\pm 89 \text{ K}$) at the middle level of crown fuel. This hot air supplied convective heating to the crown fuel and raised the branch temperature to 347 K (were shown to be repeatable to $\pm 12 \text{ K}$) which was insufficient for ignition. However, the foliage ignited so it was presumed that the temperature of foliage exceeded the ignition temperature which was approximately 523 K

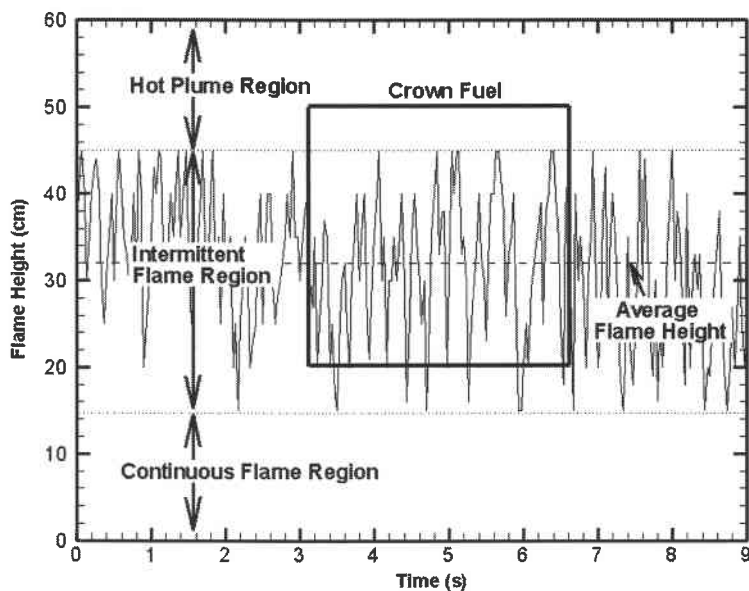


Figure 2 Illustration of variation of flame height for fire spread through excelsior surface fuel with a fuel bed depth of 0.10 m and bulk density of $3.125 \text{ kg} \cdot \text{m}^{-3}$.

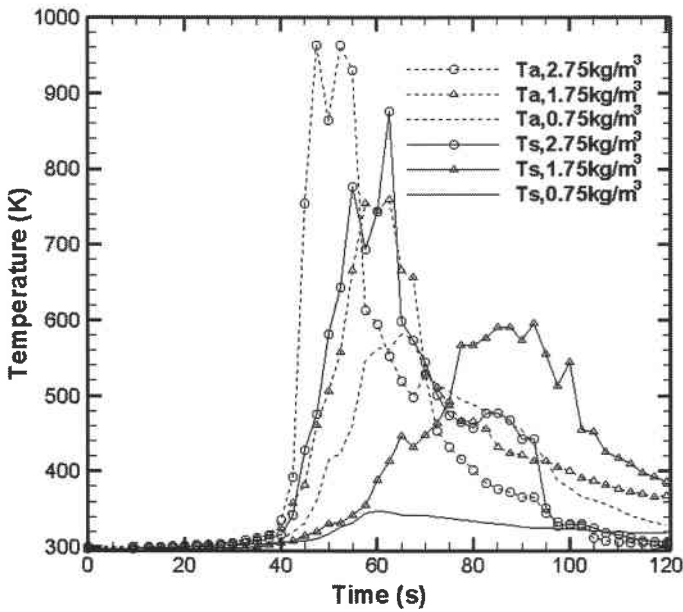


Figure 3 Time evolution of experimental air (T_a) and solid phase (T_s) temperature of the branch inside crown fuel (Crown base height is 0.20 m with bulk density of 0.75, 1.75, and $2.75 \text{ kg} \cdot \text{m}^{-3}$).

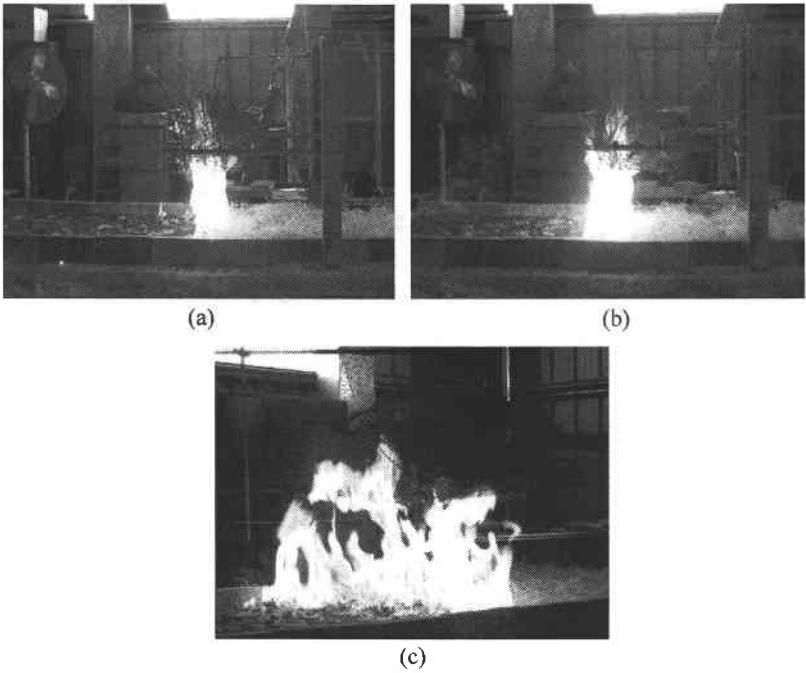


Figure 4 Illustration of flame shape when surface fire impinges on the crown base crown fuel bulk density of (a) $0.75 \text{ kg} \cdot \text{m}^{-3}$, (b) $1.75 \text{ kg} \cdot \text{m}^{-3}$, and (c) $2.75 \text{ kg} \cdot \text{m}^{-3}$ (Crown base height is 0.20 m).

(Babrauskas, 2002). Foliage burning terminated shortly after ignition due to convective cooling to the surrounding. After the surface fire passed the crown fuel, the crown fire was not sustained.

When the flame impinged on the crown fuel base for a higher crown fuel bulk density of $1.75 \text{ kg} \cdot \text{m}^{-3}$, the upward movement of hot gas was blocked by the crown fuel, causing the flame tip to spread. This effect is evident by comparing flame shape in Figure 4b with that in Figure 4a for the lower crown bulk density. The result was an increase in the average temperature at the crown fuel base, and at the middle of crown fuel, the temperature of the hot gases increased to 759 K (were shown to be repeatable to $\pm 113 \text{ K}$). The mixture of hot air and products of combustion supplied convective heating to the crown fuel raising its temperature so that it exceeded 523 K. A part of the crown fuel ignited and then switched to flaming combustion. The crown fire was successfully initiated. A similar process was found when the crown fuel bulk density increased to $2.75 \text{ kg} \cdot \text{m}^{-3}$. The flame tip spreads out as shown in Figure 4c and the temperature of hot gas inside the crown fuel increased to 967 K (were shown to be repeatable to $\pm 116 \text{ K}$). This increased convective heating to the crown fuel and the crown fuel ignited successfully. Under the same experimental conditions, repeated burning tests showed that the crown fire was initiated at crown fuel bulk densities of 1.75 and $2.75 \text{ kg} \cdot \text{m}^{-3}$, but no crown fire was observed at the lower bulk density of $0.75 \text{ kg} \cdot \text{m}^{-3}$.

Model Validation

Figures 5a, b show a comparison of the experimental temperature measurements with numerical predictions in the case of successful ignition for crown fuel bulk density of 2.75 and $1.75 \text{ kg} \cdot \text{m}^{-3}$, respectively. The numerical results show the temperature in the central portion of crown fuel at the same position as in the experimental measurement in Figure 1a. The crown base height was $Z_{cb} = 0.20 \text{ m}$. Although crown fuel was comprised of foliage and branch, only the temperature of branch was used to compare with the model results because of the practical limitation in measuring the foliage temperature. At early times, heating by radiation slowly increased the crown fuel temperature before the flame reached the base of the crown, then it rises rapidly due to additional convective heating from the surface fire. After the flame passed the base of the crown, the foliage continued to burn, releasing heat to the branch phase, which resulted in a continuous increase in branch temperature.

When branch phase temperature was sufficiently high, the branch ignited and started burning. It was noticed that the measured temperature values were lower than the calculated values. This is because the solid fuel temperature from the experiment was the measured temperature inside the branch while the actual temperature at the surface was higher. Results at the lowest crown bulk density of $0.75 \text{ kg} \cdot \text{m}^{-3}$ are presented in Figure 5c. The model results were generally consistent with the experimental results discussed earlier. In general, model predictions match the experimental results in terms of the overall trend. Since the solid fuel was modeled as a porous medium, it implied a uniform distribution within the crown fuel matrix; however the distribution was not perfectly uniform in the experiment. This difference contributed to the discrepancy in the values observed between the model and experimental results. The temperature of hot gas in the experiments was observed to be

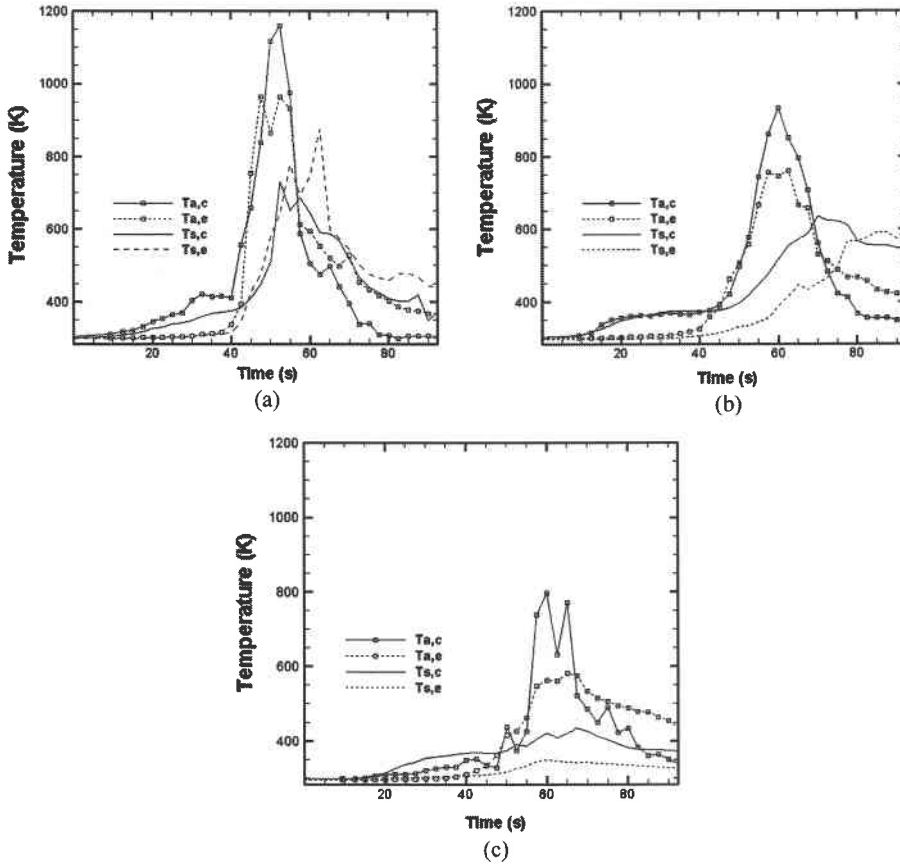


Figure 5 Time evolution of calculated air ($T_{a,c}$) and solid phase ($T_{s,c}$) temperature from the model and experimental air ($T_{a,e}$) and solid phase ($T_{s,e}$) temperature of the branch inside crown fuel with bulk density of (a) $2.75 \text{ kg} \cdot \text{m}^{-3}$, (b) $1.75 \text{ kg} \cdot \text{m}^{-3}$, and (c) $0.75 \text{ kg} \cdot \text{m}^{-3}$ (Crown base height is 0.20 m).

lower than that in the model results; specifically in the lower bulk density case. However, the difference in values between model and experimental results decreased when crown fuel bulk density increased.

Model Results

The effect of varying crown fuel bulk density was investigated in more detail using the LES model. The crown fuel bulk densities investigated in this study were 0.75, 1.75 and $2.75 \text{ kg} \cdot \text{m}^{-3}$, which corresponded to the laboratory experiments.

A successful crown fuel ignition. Figure 6a displays instantaneous 2D (vertical section at $z = 0.60 \text{ m}$) gas phase temperature contours calculated by LES at $t = 45.3 \text{ s}$ without the crown fuel above the surface fire. The figure represents data extracted from a two-dimensional plane at $z = 0.60 \text{ m}$. Velocity vectors in a vertical section (x - y) along the center of the fuel bed illustrate the direction and speed of

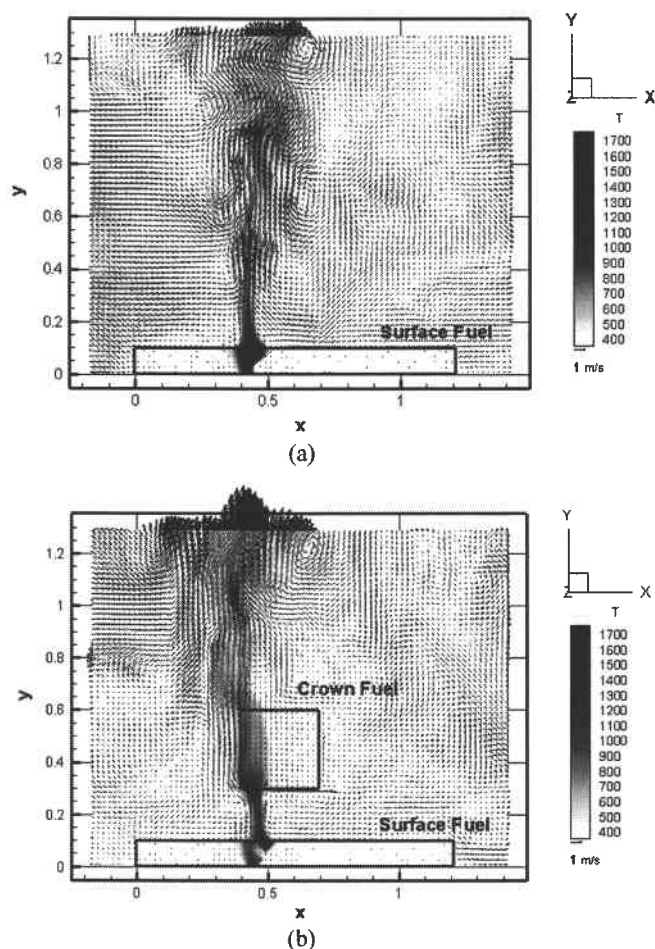


Figure 6 Instantaneous flame temperature contours and velocity vectors of surface fire spreading at time $t = 45.3$ s (a) without the crown fuel above the surface fire (b) with the crown fuel with bulk density of $1.75 \text{ kg} \cdot \text{m}^{-3}$.

fluid flow. A fire plume is formed above the surface fuel bed, and large vortical structures appear at the center and the edge of the fire plume. Ambient air was entrained into the fire plume. Inside the plume, the gas underwent an upward acceleration. The average temperature and vertical velocity of hot gas at $y = 0.30$ m are 768 K and $1.99 \text{ m} \cdot \text{s}^{-1}$, respectively. In contrast, a detailed examination in the case of a surface fire spreading under the crown fuel (with crown fuel bulk density of $1.75 \text{ kg} \cdot \text{m}^{-3}$) revealed that the hot gas velocity within the crown fuel is reduced by approximately 75%.

Figure 6b represents an instantaneous picture of the temperature distribution and velocity vectors where this effect occurs. In addition to a reduction in velocity due to higher drag from the fuel, the shape of the hot plume is modified as observed in Figure 6b. The average vertical velocity of hot gas at $y = 0.30$ m is decreased

to $0.52 \text{ m} \cdot \text{s}^{-1}$. This reduces the entrained air into the fire plume. In addition, the mixing rate of air and combustible gas also increases when the surface fire is in direct contact with the crown fuel base resulting in an increase in combustion and hence heat release rate. Thus, the average temperature of hot gas below the crown increases to 1,205 K. Since the surface fire impinges on the crown base over the course of a pulsation cycle, this allows fresh air to entrain into the bottom of the crown fuel periodically as shown in Figures 7 and 8.

Figure 7a displays instantaneous 2D (vertical section at $z = 0.60 \text{ m}$) gas phase temperature contours when the flame tip impinges on the crown base at time $t = 45.3 \text{ s}$ within a $0.50 \text{ m} \times 0.50 \text{ m}$ neighborhood surrounding the crown fuel matrix. It can be seen that the hot gas flows to the crown fuel from the bottom with the vertical velocity of $1.36 \text{ m} \cdot \text{s}^{-1}$ and temperature of 961 K. When the flame tip impinged on the crown fuel base, the hot gas velocity reduces to $0.52 \text{ m} \cdot \text{s}^{-1}$ and the temperature increases to 1,205 K. Then, it flows through the crown fuel with nearly constant

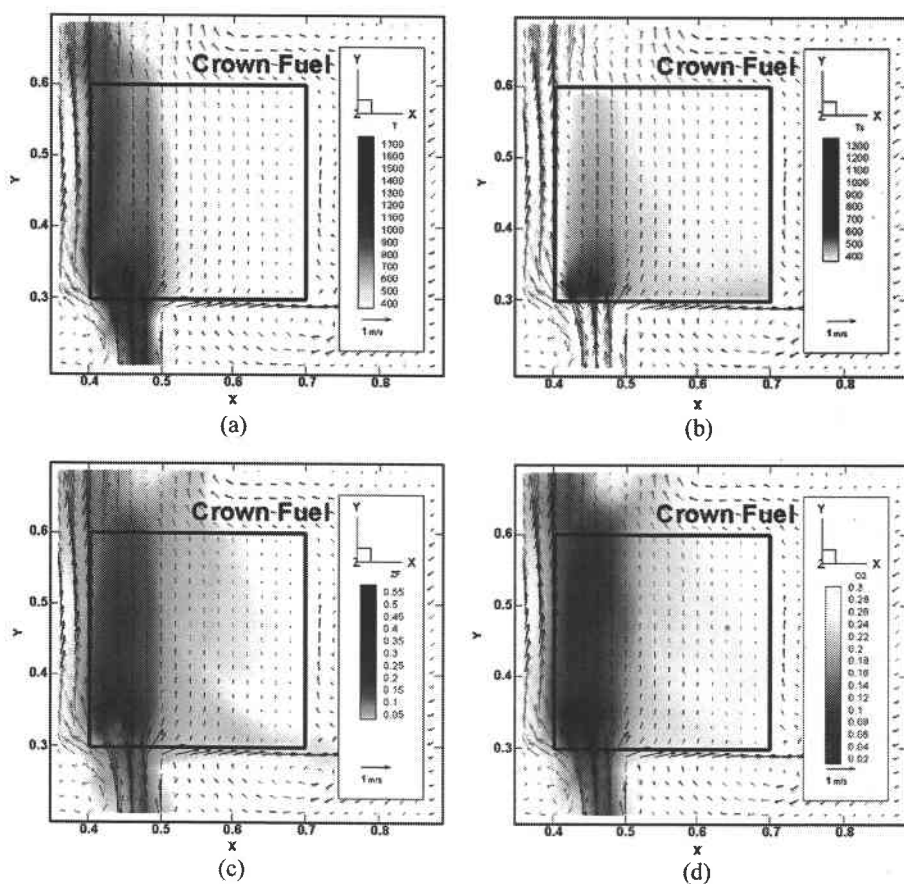


Figure 7 Instantaneous velocity vectors and contour of (a) flame temperature, (b) solid fuel temperature, (c) pyrolysis gas mass fraction, and (d) oxygen mass fraction for crown fuel bulk density of $1.75 \text{ kg} \cdot \text{m}^{-3}$ in a $0.5 \text{ m} \times 0.5 \text{ m}$ region around the crown fuel matrix when flame tip impinges on the crown base.

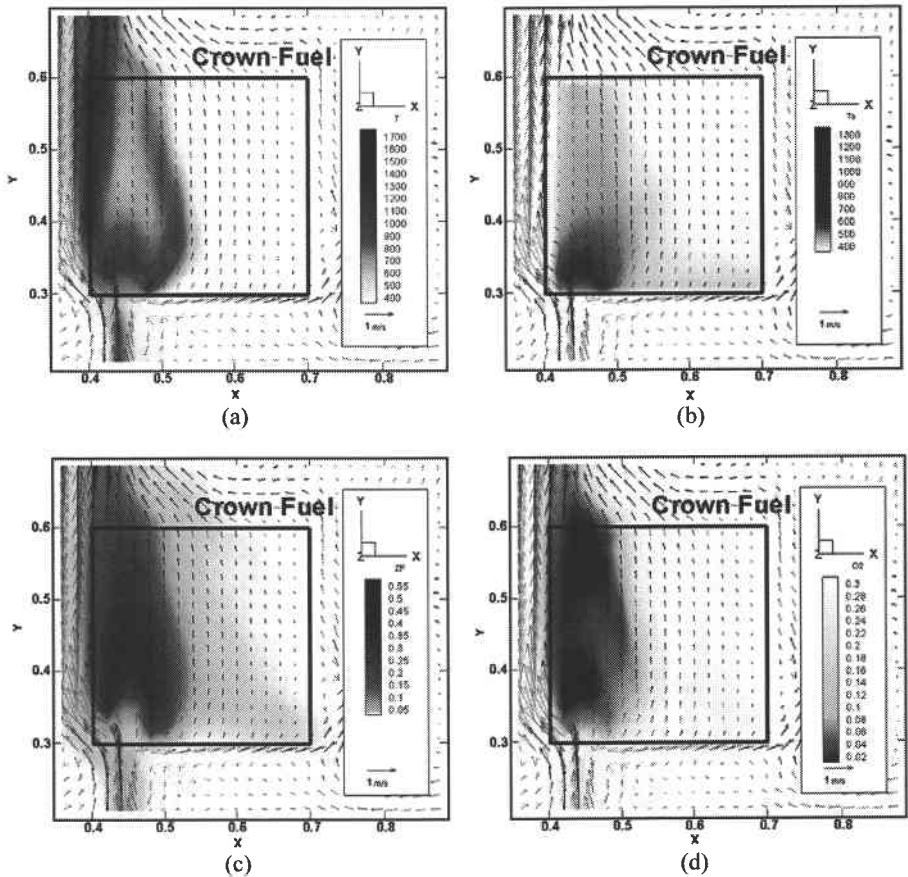


Figure 8 Instantaneous velocity vectors and contour of (a) flame temperature, (b) solid fuel temperature, (c) pyrolysis gas mass fraction, and (d) oxygen mass fraction for crown fuel bulk density of $1.75 \text{ kg} \cdot \text{m}^{-3}$ in a $0.5 \text{ m} \times 0.5 \text{ m}$ region around the crown fuel matrix when flame height decreases and flame tip does not reach the crown base due to the pulsation of surface fire.

vertical velocity. Thus, most of the hot gas is accumulated in the bottom part of the crown fuel. At this instant, it is noticed that the flame tip spreads out so that the hot gas flow covers a large area of the solid fuel.

The hot gas temperature in the bottom portion of crown fuel increases to 1,035 K and it mainly transfers heat to the solid fuel. This results in high average solid fuel temperature of 546 K (with the average foliage and branch temperature of 831 K and 431 K, respectively) in the bottom part of crown fuel as shown in the solid fuel temperature contours in Figure 7b. This accelerates the pyrolysis process of solid fuel in this area. Figures 7c, d display instantaneous 2D (vertical section at $z = 0.60 \text{ m}$) mass fraction contours of pyrolysis gas and oxygen, respectively. It can be seen that hot gas flows into the crown fuel with a pyrolysis gas mass fraction of 6.76% (from surface fire) with an oxygen concentration of 13.99%. Then, the pyrolysate gases are released from the surface of solid fuel in the bottom part of

crown fuel and combine with the hot gas flow so the mass fraction of pyrolysis gas increases to 22.66%. With sufficient heat and oxygen, foliage ignites and leads to flaming combustion of pyrolysate gases above it. The oxygen inside the combustion zone is consumed so the oxygen concentration inside this zone decreases to 4.60%. This implies that it is a fuel-rich combustion in which the combustion rate is controlled by the air supplied to the flame.

Figure 8a displays instantaneous gas phase temperature contours when the flame height decreases and flame tip does not reach the crown base at a later time that is $1/2$ of a time period for a full cycle of oscillation, past the time corresponding to Figure 7. In Figure 8a, the hot gas flows to the crown fuel from the bottom with the vertical velocity of $1.03 \text{ m} \cdot \text{s}^{-1}$ and reduces to $0.39 \text{ m} \cdot \text{s}^{-1}$ when entering into the crown fuel base. It is clear that fresh air entrains into the bottom of crown fuel and provides the convective cooling to this region. The vortical structures that provide this flow are evident from the velocity field. The hot spot occurs inside the crown fuel instead of at the crown base. The hot gas temperature in this region thus reduces to 984 K. However, the solid fuel temperature continues to increase to 570 K (with the average foliage and branch temperature of 1,085 K and 460 K, respectively) as shown in the foliage temperature contours in Figure 8b, so the pyrolysis process of solid fuel continues.

At this instant, the hot gas flows into the crown fuel with relatively high oxygen mass fraction of 18.54%. This accelerates the combustion rate because it is observed that the flame front at the bottom propagates downstream through the fuel-rich area as shown in pyrolysis mass fraction contours in Figure 8c. The oxygen concentration inside the combustion zone is quickly depleted to 1.78%. This is due to consumption by the fire as revealed through the oxygen mass fraction contour in Figure 8d. As a result, there are excess pyrolysate gases (with mass fraction of 31.89%) available within the crown fuel matrix. Therefore, flaming combustion can be sustained.

Figure 9a shows the time evolution of the calculated foliage temperature (T_s) at $x = 0.55 \text{ m}$ and $y = 0.45 \text{ m}$ for crown fuel bulk density of $1.75 \text{ kg} \cdot \text{m}^{-3}$. It also shows

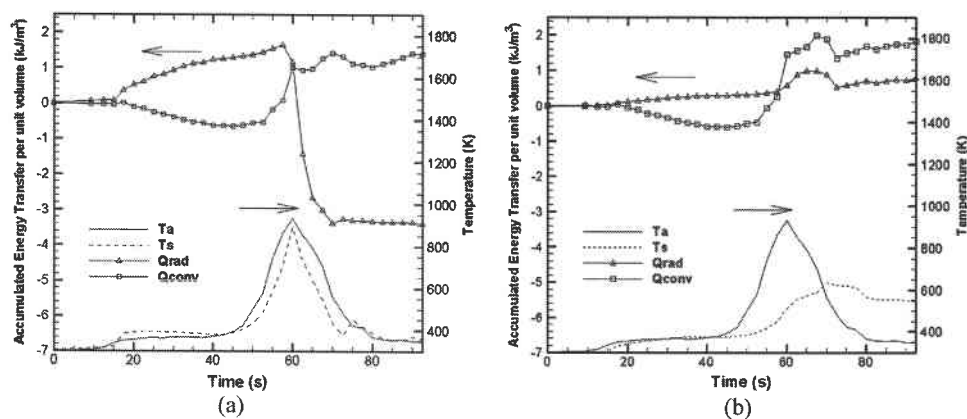


Figure 9 Time evolution of gas (T_a) and solid phase (T_s) temperature and energy per unit volume absorbed (Q_{rad} and Q_{conv}) by solid particle located at located at $x = 0.55 \text{ m}$ and $y = 0.45 \text{ m}$ of (a) foliage and (b) branch with crown bulk density $1.75 \text{ kg} \cdot \text{m}^{-3}$.

the time evolution of accumulated energy per unit volume absorbed or released by foliage through convective (Q_{conv}) and radiative (Q_{rad}) heat transfer between solid and gas phase. The accumulated value of heat transfer variables was computed by integrating their instantaneous rates per unit volume over time. At early times, foliage temperature increases by radiation before the flame reaches the base of the crown. Since the temperature of the gas phase is lower than that of the solid phase, convective cooling leads to a decrease in the energy absorbed by convective heating in this preheating region.

When the flame reaches the base of the crown at $t = 45.0$ s, the gas temperature is higher than solid fuel temperature. The foliage is heated by convection causing its temperature to rise. When the temperature reaches the ignition point at $t = 67.0$ s, it starts to ignite and its temperature rises rapidly, consequently, the solid particle loses heat through radiation and therefore the absorbed energy decreases due to radiative loss. Combustion continues for a short time to $t = 73.0$ s, then, the burning is completed and leaves non-combustible hot ash. The time evolution of the calculated branch temperature and accumulated energy per unit volume by branches at $x = 0.55$ m and $y = 0.45$ m, is shown in Figure 9b. During the preheating phase ($t = 0.0$ – 45.0 s), branch temperature (T_s) increases slowly by radiation heating. Then, it increases rapidly at $t = 57.0$ s by additional radiative and convective heating from foliage combustion. Thus, the branch temperature continues to increase until it reaches ignition temperature at $t = 68.0$ s, and then it starts to ignite.

Effects of crown fuel bulk density. In the crown fuel ignition process, hot gases from the surface fire are forced to pass through the crown fuel and then transfer convective heat into the crown fuel. Since the crown fuel bulk density influences this flow, it affects the heat transfer to the crown fuel particles and eventually

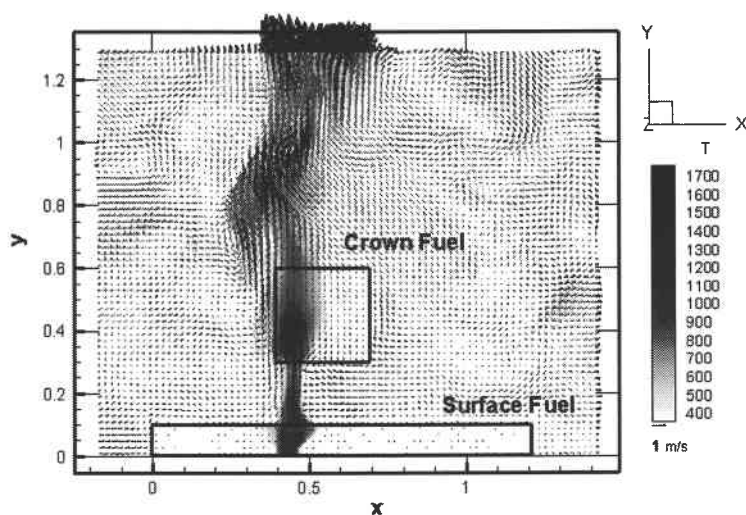


Figure 10 Instantaneous flame temperature contours and velocity vectors at time $t = 45.4$ s with crown bulk density $0.75 \text{ kg} \cdot \text{m}^{-3}$.

the ignition of crown fuel. For the unsuccessful ignition case, Figure 10 displays instantaneous 2D (vertical slice at $z = 0.60$ m) gas phase temperature contours in one half of a computational domain calculated by LES at time $t = 45.4$ s.

In this case, the average vertical velocity of hot gas at $y = 0.30$ m is $0.97 \text{ m} \cdot \text{s}^{-1}$ and the average temperature of hot gas below the crown is 516 K . The vertical velocity in this case is higher than that in the case of higher crown fuel bulk density of $1.75 \text{ kg} \cdot \text{m}^{-3}$ due to less drag force induced by solid fuel. The higher velocity results in more air entrained into the fire plume, thus the hot gas temperature in this case is lower than that in the case of higher crown fuel bulk density. This implies that more convective cooling of the crown fuel occurs due to heat loss to the surrounding flow. Thus, the potential for ignition is decreased due to the lower hot gas temperature and the higher convective cooling to the surroundings.

Figure 11a displays the instantaneous 2D (vertical slice at $z = 0.60$ m) gas phase temperature contours when the flame tip impinges on the crown base at time

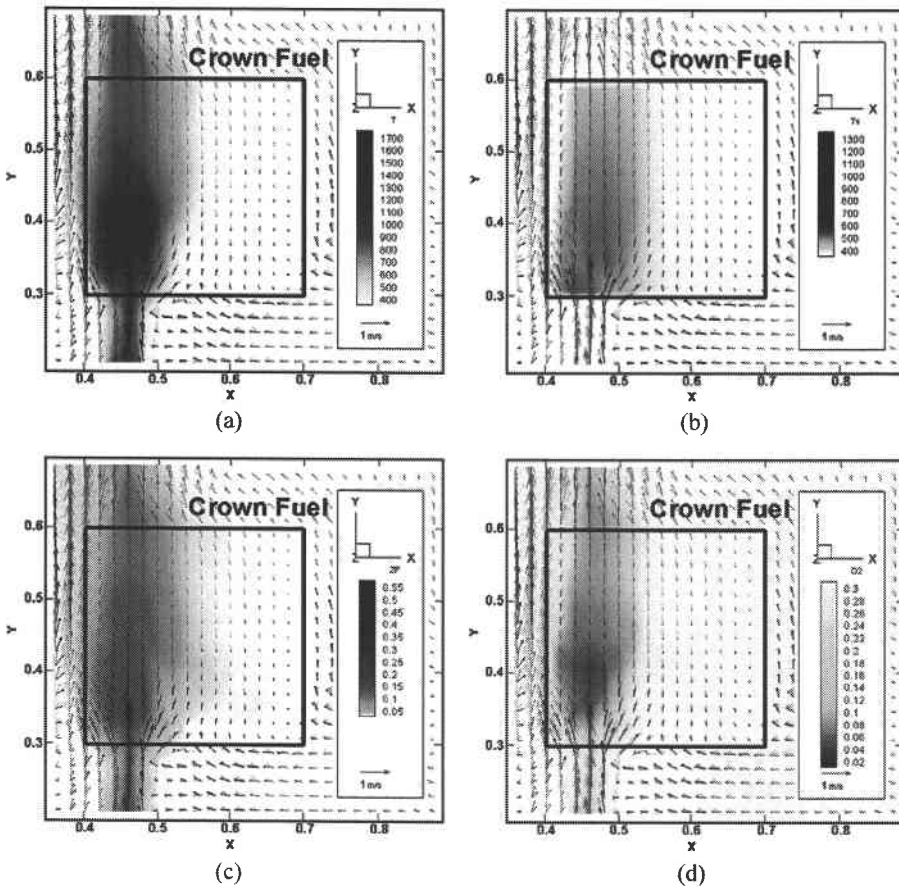


Figure 11 Instantaneous velocity vectors and contour of (a) flame temperature, (b) solid fuel temperature, (c) pyrolysis gas mass fraction, and (d) oxygen mass fraction for crown fuel bulk density of $0.75 \text{ kg} \cdot \text{m}^{-3}$ in a $0.5 \text{ m} \times 0.5 \text{ m}$ region around the crown fuel matrix when flame tip impinges on the crown base.

$t = 45.4$ s. The hot gas flows to the crown fuel from the bottom with the vertical velocity of $1.26 \text{ m} \cdot \text{s}^{-1}$ with temperature of 624 K. Unlike the higher bulk density case, the velocity of hot gas decreases only slightly to $0.93 \text{ m} \cdot \text{s}^{-1}$ with the temperature decreasing to 687 K when hot gas flows through the bottom part of the crown fuel. However, the velocity of hot gas decreases quickly to $0.58 \text{ m} \cdot \text{s}^{-1}$ as it reaches the upper portion of crown fuel. Thus, the hot gas is not accumulated in the bottom part of the crown fuel, but it intends to be accumulated in the upper portion instead. In this case, the flame tip spreads out laterally so the hot gas flow covers less area of the solid fuel than that in the case of higher bulk density.

The temperature of solid fuel increases along the flow path of hot gas to 493 K (with the average foliage and branch temperature of 789 K and 410 K, respectively) as shown in the solid fuel temperature contours in Figure 11b. Since the temperature of solid fuel is relatively low, there are small traces of pyrolysate gases that are released from heated solid fuel as shown in the pyrolysis gas mass fraction contours in Figure 11c. In this case, the hot gas flows through the crown fuel with a pyrolysis gas mass fraction of 8.87% (from surface fire mainly) which is much lower than that in the higher bulk density case. Accordingly, there is no foliage ignition because of insufficient fuel. In Figure 11d, it can be seen that the oxygen concentration decreases only slightly as a result of surface fire combustion, so it is much higher than in the higher bulk density case.

Figure 12a displays instantaneous 2D (vertical section at $z = 0.6 \text{ m}$) gas phase temperature contours when the flame height decreases and the flame tip does not reach the crown base at $1/2$ a time period later. It can be seen that the entrained air flows into the crown from the bottom with the vertical velocity of $0.99 \text{ m} \cdot \text{s}^{-1}$ and the temperature of 477 K. It forces the hot gas to flow upward. Since no hot gas is accumulated in the lower part of crown fuel, the entrained air can flow pass through the crown fuel with a low temperature of 657 K and a relatively high vertical velocity of $0.70 \text{ m} \cdot \text{s}^{-1}$. Therefore, the average hot gas temperature from the surface fire, at the bottom part of the crown fuel, is lower than that in the higher bulk density case. This decreases the convective heating rate and therefore the solid fuel temperature at the bottom part of crown fuel is 484 K (with the foliage and branch temperature of 713 K and 417 K, respectively) which is lower than that in the higher bulk density case. However, little hot gas is accumulated at the top of crown fuel with the temperature of 1,139 K.

It transfers heat to solid fuel so the solid fuel temperature increases to 519 K (with the foliage and branch temperature of 748 K and 413 K, respectively) in this area as shown in the solid fuel temperature contours in Figure 12b. At this moment, the hot gas flows through the crown fuel with a pyrolysis gas mass fraction of 4.67% (from surface fire mainly). Then, the pyrolysate gases are released from the surface of solid fuel in the upper part of crown fuel so the mass fraction of pyrolysis gas increases to 13.63% as shown in the pyrolysis mass fraction in Figure 12c. Since the pyrolysate gases are sufficient, flaming combustion of the pyrolysate gases forms in the upper portion of the crown fuel and consumes oxygen inside the combustion zone as shown in the oxygen mass fraction in Figure 12d. Since the combustion cannot overcome the convective cooling to the surrounding, the temperature of solid fuel around combustion zone starts to decrease and flaming combustion terminates shortly. In addition, it is noticed that hot gas forces all pyrolysate gases to flow out

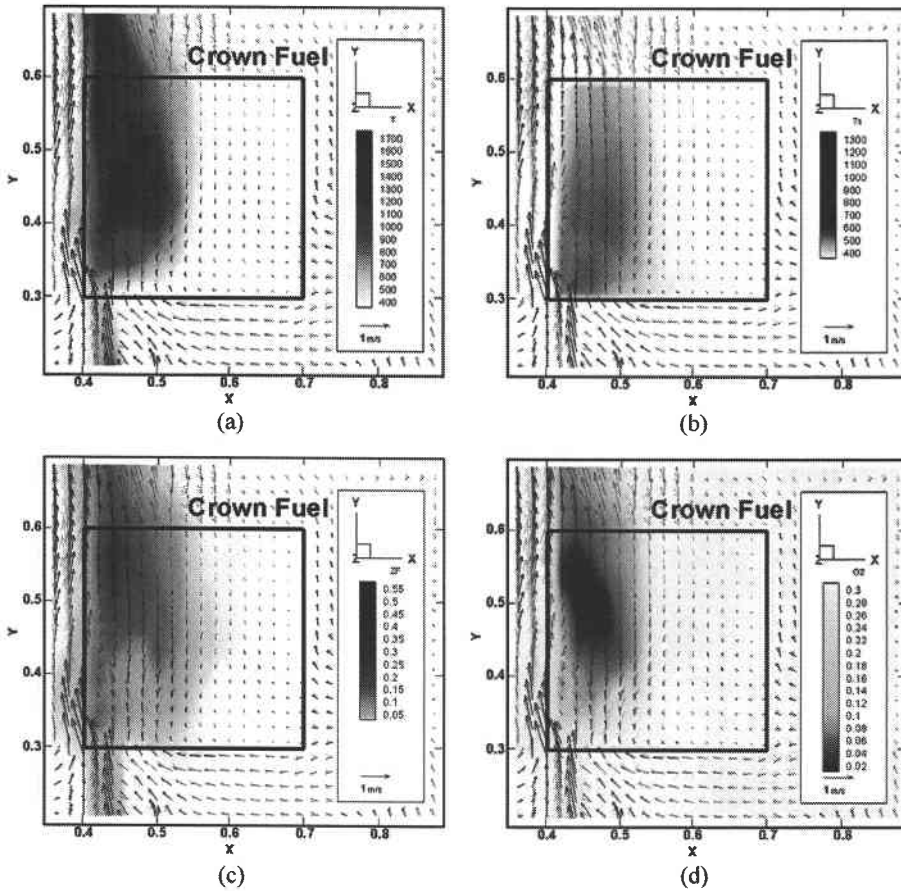


Figure 12 Instantaneous velocity vectors and contour of (a) flame temperature, (b) solid fuel temperature, (c) pyrolysis gas mass fraction, and (d) oxygen mass fraction for crown fuel bulk density of $0.75 \text{ kg} \cdot \text{m}^{-3}$ in a $0.5 \text{ m} \times 0.5 \text{ m}$ region around the crown fuel matrix when flame height decreases and flame tip does not reach the crown base due to the pulsation of surface fire.

from the crown fuel matrix. Therefore, crown fire initiation is considered to be unsuccessful.

Figure 13a shows the effect of bulk density on time evolution of the calculated foliage temperature (T_s) and heat absorbed by foliage (Q_{rad} and Q_{conv}) at $x = 0.55 \text{ m}$ and $y = 0.45 \text{ m}$. At early times, all cases are almost identical. The variation is noticed when the flame reaches the base of the crown at $t = 40.0 \text{ s}$. Since the flame tip spreads out more in the higher bulk density case than in the lower bulk density case, the hot gas covers a larger area and reaches the center of crown fuel at the earlier time. It can be seen that the hot gas reaches the center of crown fuel at 40.0, 45.0, and 48.0 s, respectively, for the crown fuel bulk density of 2.75, 1.75, and $0.75 \text{ kg} \cdot \text{m}^{-3}$.

Since the hot gas temperature due to surface fire in the higher bulk density case is higher than that in the lower bulk density case, more convective heat can be

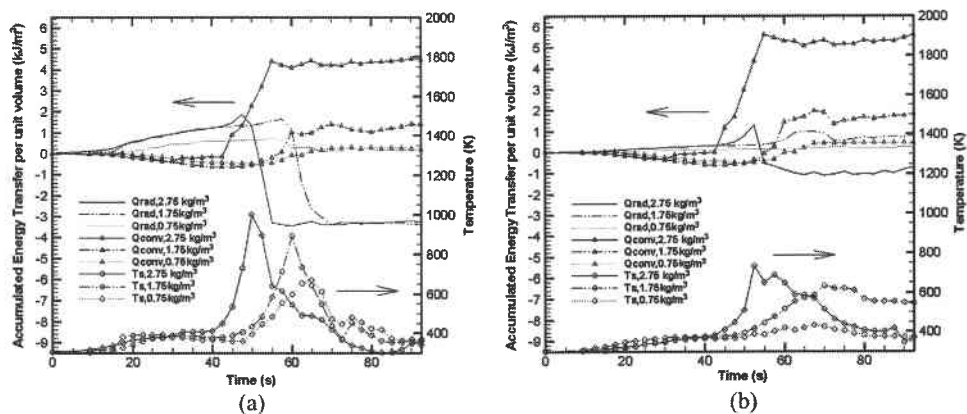


Figure 13 Time evolution of solid phase (T_s) temperature and energy per unit volume absorbed (Q_{rad} and Q_{conv}) by solid particle located at $x = 0.55$ m and $y = 0.45$ m with different crown fuel bulk density of 0.75, 1.75 and $2.75 \text{ kg} \cdot \text{m}^{-3}$ for (a) foliage and (b) branch.

transferred to the foliage. The convective energy absorbed by the foliage is 0.81, 2.60 and $4.83 \text{ kJ} \cdot \text{m}^{-3}$, respectively, for the crown fuel bulk density of 0.75, 1.75, and $2.75 \text{ kg} \cdot \text{m}^{-3}$. Thus, the increase in temperature of the foliage in the higher bulk density case is considerably higher than that in the case of lower bulk density. When foliage starts to ignite, its temperature rises rapidly therefore it loses heat through radiation. The radiative energy released from the foliage is 0.78, 4.89, and $5.31 \text{ kJ} \cdot \text{m}^{-3}$, respectively, for the crown fuel bulk density of 0.75, 1.75, and $2.75 \text{ kg} \cdot \text{m}^{-3}$. It can be seen that the radiative energy released from the case with higher bulk density is much higher. This is because the increase in bulk density results in higher fire intensity which arises from a greater amount of pyrolysis gases accumulated inside the crown fuel matrix.

The higher bulk density also prevents convective cooling from the surroundings and helps to retain energy within the crown fuel. In addition, higher bulk density also means more solid fuel for combustion. Thus, the fire can be sustained for a longer time in higher bulk density case. This affects the success of crown fire initiation because the heat that is released from the foliage combustion is transferred to the fuel particle located apart including the branch. If the flaming combustion can be sustained long enough, it will burn all fuel particles within crown fuel matrix. Figure 13b shows the effect of bulk density on time evolution of calculated branch temperature (T_s) and heat absorbed by foliage (Q_{rad} and Q_{conv}) at $x = 0.55$ m and $y = 0.45$ m. It is clear that the branch, in the higher bulk density case, not only absorbs convective heat, but it also absorbs radiative heat from foliage combustion. Thus, it ignites since the total heat transfer to the branch is sufficiently high. For the lower bulk density case, since the foliage combustion cannot be sustained, there is no additional radiative heat transfer to the branch. Thus, the heat transfer to the branch is insufficient for ignition.

For the current experimental conditions, it is clear that higher crown fuel bulk density enhances the possibility of crown fire initiation. As the bulk density increases, the drag force on the flow of hot gas increases so that the hot gas flowing

though the crown fuel matrix is decelerated. This implies that the difference between the thermal energy flow into the crown fuel matrix and the thermal energy flow out from the crown fuel matrix increases. Thus, more thermal energy is accumulated within the crown fuel layer. This increases the temperature of hot gas and accelerates the pyrolysis process of solid fuel. The higher bulk density also helps to retain the pyrolysis gas within the crown fuel matrix. Therefore, the possibility of crown fire initiation increases when crown fuel bulk density increases.

It is noted that if the crown bulk density increases beyond this range, the possibility of crown fire initiation still increases until the crown bulk density reaches an upper limit in which the hot smoke from surface fire cannot flow through the crown fuel; then the possibility of crown fire initiation decreases. In our preliminary experiments, it was found that the crown fire was initiated successfully at a crown bulk density of $6.79 \text{ kg} \cdot \text{m}^{-3}$ even though the moisture content was 84% (compared to 44% in this study). However, it was not initiated for a crown bulk density of $7.92 \text{ kg} \cdot \text{m}^{-3}$ (for a moisture content of 84%). It was observed that the hot smoke from the surface fire could not flow through the crown fuel so less thermal energy was transferred to the crown fuel matrix. Nevertheless, this situation is encountered only if the crown bulk density is much higher than the typical value for chaparral.

Rothermel's surface fire model (Rothermel, 1972) specifies the effective bulk density as the bulk density of the fuel multiplied by the efficiency of heating. Since fine fuel has a higher surface area-to-volume ratio, it can absorb more convective/radiative energy from the hot gas. Thus, it has a higher efficiency of heating. For crown fire, the effective bulk density proposed by Rothermel is a measure of the tendency of the crown fuel to be ignited or consumed. For the current experimental conditions, the results agree well with Rothermel's concept in which the efficiency of heating is related to the fuel particle size. However, the fuel particle size not only influences the surface area-to-volume ratio, it also affects the drag force. A higher drag force helps in retaining the thermal energy/fuel gas within the crown fuel layer.

CONCLUSION

The effect of crown fuel bulk density on crown fire initiation was investigated through experiments and numerical modeling. Experimental results indicated that propagation of surface fire through excelsior fuel beds led to ignition of crown fuel comprised of live chamise under conditions wherein the crown base height is located within either the continuous or intermittent flame regimes. A Large Eddy Simulation approach was used to simulate the transition from surface to crown fire in shrub fuels where canopy heights range from 1.00 m to 3.00 m, crown base height ranges from 0.60 m to 1.00 m, and bulk densities range from 0.20 – $2.10 \text{ kg} \cdot \text{m}^{-3}$. The results predicted by a LES approach, for chamise crown fuel bulk densities of 0.75, 1.75 and $2.75 \text{ kg} \cdot \text{m}^{-3}$, were in reasonable agreement with the experimental measurements. Under the current experimental conditions, it was found that higher crown fuel bulk density enhances the possibility of crown fire initiation. Increasing crown fuel bulk density increased the capability to retain thermal energy inside the crown fuel matrix while reducing convective cooling to the surrounding. The findings are based on a limited set of experimental conditions, and correspondingly, a limited set of

computational results. However, these represent a first step in better understanding the phenomenon of transition of a surface fire to a crown fire in shrublands.

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