

## EXPERIMENTAL AND NUMERICAL MODELING OF SHRUB CROWN FIRE INITIATION

Watcharapong Tachajapong,<sup>1</sup> Jesse Lozano,<sup>1</sup> Shankar Mahalingam,<sup>1</sup> Xiangyang Zhou,<sup>1</sup> and David R. Weise<sup>2</sup>

<sup>1</sup>Department of Mechanical Engineering, University of California, Riverside, California, USA

<sup>2</sup>Forest Fire Laboratory, Pacific Southwest Research Station, USDA Forest Service, Riverside, California, USA

*The transition of fire from dry surface fuels to wet shrub crown fuels was studied using laboratory experiments and a simple physical model to gain a better understanding of the transition process. In the experiments, we investigated the effects of varying vertical distances between surface and crown fuels (crown base height), and of the wind speed on crown fire initiation. The experimental setup was designed to model an isolated clump of crown fuel such as a single tree or group of shrubs. Three wind velocities (0, 1.5, and 1.8 m · s<sup>-1</sup>) and three crown base heights (0.20, 0.30, and 0.40 m) were used. Crown fuel (solid) and the air temperature within the elevated fuel bed were measured. Crown bulk density and fuel moisture content were held constant in all the experiments. As crown base height increased, crown fire initiation success decreased. Non-zero wind speeds reduced crown fire initiation success because of reduced heating. A simple physical model based on convective and radiative heat exchanges was developed to predict crown fire initiation above a surface fire. The predicted results for different wind speeds and crown base heights were in good agreement with the experimental measurements. Because of its relative simplicity and inclusion of basic physics, it is anticipated that the model can be readily applied and/or adapted to model diverse fuel configurations.*

**Keywords:** Crown fire; Transition

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Watcharapong Tachajapong is presently in the Department of Mechanical Engineering, Chiang Mai University, Thailand. Xiangyang Zhou is presently at FM Global, Norwood, Massachusetts, USA.

Address correspondence to Watcharapong Tachajapong, Department of Mechanical Engineering, Chiang Mai University, Chiang Mai, Thailand. E-mail: wtacha@chiangmai.ac.th

## INTRODUCTION

Crown fire is a wildland fire that spreads in the elevated foliage and branches at a rate much faster than a surface fire (Rothermel, 1983). It is thus very difficult to control (Albini & Stocks, 1986). Crown fire models are classified as either crown fire initiation or spread models (Pastor et al., 2003), and much attention has been focused on modeling crown fire in coniferous forests around the world (Albini & Stocks, 1986; Butler et al., 2004; Grishin & Perminov, 1990; Van Wagner, 1977). In southern California, crown fires occur in shrublands ("chaparral") and cause significant damage frequently (Philpot, 1977). Fuel bed parameters that influence crown fire dynamics, including canopy height, crown base height, and crown bulk density, may be very different in shrublands as compared to conifer forests (Tachajapong et al., 2008). Hence, a crown fire model is necessary to predict and manage fire risks in these areas. In this paper, the focus is on the process of transition from surface to crown fire for shrub canopy fuels. Successful transition from a surface fire to a crown fire occurs when the net amount of thermal energy produced by the surface fire is transferred to the crown fuel by convection and radiation, resulting in an increase in crown fuel temperature, followed by ignition and sustained fire spread. Due to its inherent complexity, no complete physical model of crown fire initiation exists. Current operational models rely on a semi-empirical approach to predict the onset of crown fire in conifer forests (e.g. Douglas-fir, Ponderosa pine, mixed conifer, and Lodgepole pine). Most of them are based on convection theory in which the ignition of crown fuel is dependent on the convective energy released from surface fire (Alexander, 1998; Scott & Reinhardt, 2001; Van Wagner, 1977; Xanthopoulos, 1990). These semi-empirical models that neglect the detailed crown fuel structure have been moderately successful in predicting crown fire initiation in conifer forests. Because the net energy transfer to the crown fuel is dependent on both the heat released from surface fire (heat source) and the heat absorbed by crown fuel (heat sink), this approach is deficient to accurately predict the ignition of diverse crown fuel configurations (e.g., shrub canopy fuel). Thus, a semi-empirical model based on heat transfer theory was developed by Cruz et al. (2006a, 2006b, 2006c) by using the characteristics of surface fire as a heat source and characteristics of crown fuel as a heat sink. Ignition is predicted if the simulated temperature of crown fuel reaches ignition temperature. Detailed crown fuel characteristics (i.e., fuel particle surface area-to-volume ratio, specific heat of fuel particles, fuel mass density, foliage moisture content, and the lower boundary of the canopy fuel layer) determine the energy absorbed by crown fuel. Therefore, this approach is applicable, and was adapted and implemented for investigating the ignition of shrub canopy crown fuel. Crown fuel bulk density refers to the oven dry mass of foliage and small twig (less than 3 mm in diameter) per unit volume of canopy (Alexander, 1988; Finney, 1998; Keane et al., 2005; Van Wagner, 1977). The canopy height is the greatest 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 & Reinhardt, 2001). Finally, fuel moisture content refers to the ratio of mass of water in the fuel to dry fuel mass.

A simplified, repeatable, laboratory-scale experiment was designed to systematically observe the transition from a surface fire to a crown fire. The usefulness of laboratory-scale fire experiments can be questionable, as they may not be completely relevant to field situations (e.g., differences in surface fire intensity and behavior and complicated interactions between surface fire and crown fuel). However, carefully designed laboratory experiments can facilitate the study of specific effects by providing a better control of key variables. Williams (1969) identified several dimensionless groups that should be considered for scaling fire phenomena. However, it is nearly impossible to match all of them simultaneously with available experimental facilities. Quintiere (1989) described three scaling techniques that have been used effectively in fire research: Froude number scaling, pressure scaling, and analog scaling. Froude number scaling focuses on maintaining the right balance between convective and gravitational processes in the experiment and is preserved when experiments are conducted using normal ambient air. Pressure scaling is achieved by conducting experiments under controlled ambient pressure so that Reynolds number similarity can be preserved by scaling diffusive effects. Analog scaling offers the advantage of ease of visualization of high Reynolds number flow by using two different fluids to simulate the buoyant effects. For example, water may be used to simulate ambient air, while a different fluid (e.g., salt) is used to simulate a heat source.

The focus of the current study is on examining the influence of wind on shrub canopy crown fire initiation by focusing on the energy transfer processes to the crown fuel. Therefore, it is important to consider the hot gas movement originating from a surface fire as it affects convective energy transfer directly. Consequently, laboratory experiments were designed to preserve Froude number similarity. Because the Reynolds number was not preserved, the surface fire behavior in the experiments was not dynamically similar to the real fires. Nevertheless, these laboratory-scale experiments can be used to observe the trend of heat transfer processes and help identify key variables that can be studied in relatively more expensive, and typically less accessible, high intensity fire experiments. In this study, the experiments were designed for the purposes of investigating the effects of varying crown base height and wind speed on shrub canopy ignition. A simple semi-empirical model based on fundamental heat transfer principles was used to predict the possibility of crown fire initiation by predicting the temperature of the crown fuel. The experiments described in this paper serve as a useful platform for verifying model predictions.

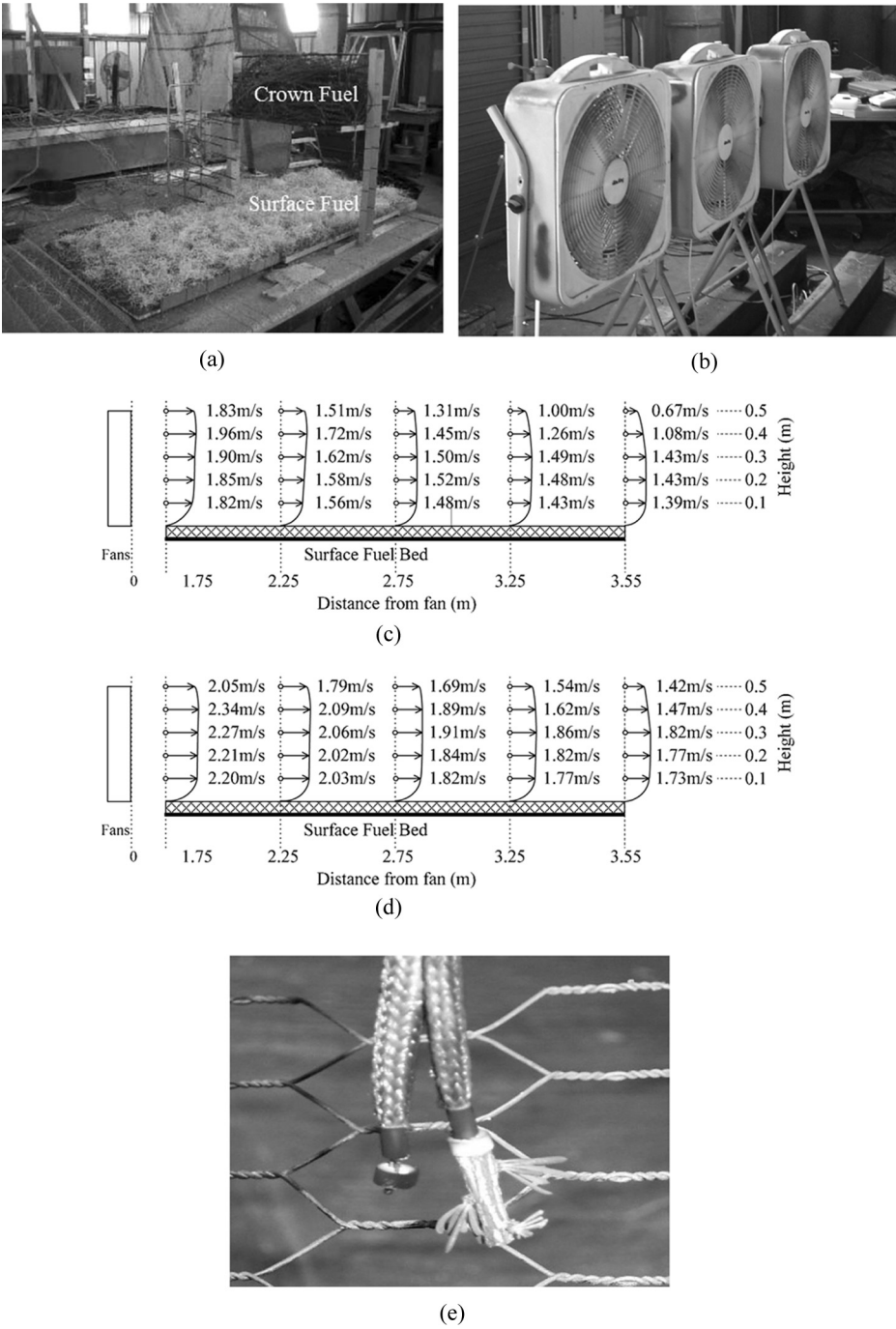
## DESCRIPTION OF EXPERIMENTAL SETUP

A laboratory-scale experimental setup was designed to investigate the effects of varying crown base height and wind speed on the process of transition of a surface fire to a crown fire in shrublands. It was specifically designed for the purposes of validating simplified semi-empirical models and more complicated physical models. One important requirement was that the experiments had to be repeatable to minimize uncertainty in experimental data. This requirement accomplishes two important outcomes. First, it ensures the accuracy of input required for any model, and second, model predictions may be compared with greater confidence to experimental results. In vegetation complexes subject to crown fire, there is often a non-uniform vertical

distribution of fuel in the space between the surface and crown fuels. To simplify modeling, it was assumed that there is no vertical continuity in fuels from the surface to the base of the crown (“fuel ladder”), and experimentally modeled a gap between surface and crown fuels, following Albini (1996), as shown in Figure 1a.

A mass of 0.45 kg of aspen (*Populus tremuloides*) excelsior with fuel particle diameter of 1.0 mm, evenly distributed over the entire 0.8 m × 1.8 m surface to a depth of 0.1 m, represented the surface fuel. Characteristics of surface fuels (loading, depth, continuity) in chaparral stands have high spatial variability that is influenced by slope, species composition, canopy density, rainfall, and other microenvironmental factors. The bulk density, fuel particle density, surface-to-volume ratio, moisture content, heat of char combustion, char content, and ash content of the excelsior were 3.13 kg · m<sup>-3</sup>, 400 kg · m<sup>-3</sup>, 4,000 m<sup>-1</sup>, 18%, 32.37 MJ · kg<sup>-1</sup>, 15.40%, and 0.35%, respectively (Susott, 1982). The surface fuel was ignited along a line parallel to its width of 0.8 m. To ensure rapid ignition, approximately 2 ml of ethyl alcohol were sprayed uniformly over this width. Ignition was accomplished at the center of the line with a hand-held igniter, and a line fire was established in less than a second. The effect of varying the horizontal distance between the crown fuel and the ignition zone, referred to as the preheating length, was examined by using two preheating lengths, 0.30 m and 1.00 m. Under the same nominal experimental conditions, repeated tests showed that the effect of preheating length on radiative preheating and on crown fire initiation was small. However, a preheating length of 1.0 m was chosen to ensure that the surface fire did not tilt and spread past the crown fuel matrix too quickly in wind-aided cases.

Live chamise (*Adenostoma fasciculatum*) with foliage diameter of approximately 0.5 mm and branch diameter of approximately 3.5 mm comprised the fuel bed. The mass proportions of foliage and branch were 53% and 47%, respectively. The physical properties of foliage were 500 kg · m<sup>-3</sup>, 8,000 m<sup>-1</sup>, 84%, 31.35 MJ · kg<sup>-1</sup>, 28.60%, and 3.50%, respectively, for the fuel particle density, surface-to-volume ratio, moisture content, heat of char combustion, char content, and ash content (Susott, 1982). The corresponding properties for the branch phase were 600 kg · m<sup>-3</sup>, 1,143 m<sup>-1</sup>, 84%, 31.35 MJ · kg<sup>-1</sup>, 14.30%, and 0.50%, respectively (Ragland et al., 1991; Susott, 1982). All chamise samples were approximately the same size, and were collected from the same field location in Riverside County, California, and were arranged in a volume with dimensions 0.30 m × 0.30 m × 0.80 m in height, depth and width. The crown fuel was placed on a coarse wire mesh with 2.54 cm hex size (~1 × 1 mesh per inch). The wire 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 relatively unimpeded except for the presence of the crown fuel. An important property of the crown fuel matrix is crown fuel bulk density. In a highly compact crown, the fuel elements are closely packed together and fuel bulk density is higher, whereas in a less compact crown, the individual fuel elements are spaced farther apart. Higher crown fuel bulk density may increase the possibility of crown fire initiation by increasing the thermal energy accumulated within the crown fuel matrix and reducing convective energy loss to the surroundings (Tachajapong et al., 2008). Thus, a high value for the crown fuel bulk density was chosen in this study to increase the possibility of crown fire initiation under the presence of wind and to reduce the impact of convective energy loss. Initial repeated



**Figure 1** The experimental setup. The excelsior fuel bed and crown fuel are shown in (a). A set of fans used to generate wind is shown in (b), and the wind speed profiles in the direction of wind for low and high wind speed are shown in (c) and (d), respectively. Thermocouples utilized for temperature measurements are shown in (e).

burning tests were carried out for a range of high crown fuel bulk densities of  $6.8\text{--}7.9\text{ kg}\cdot\text{m}^{-3}$ . It was observed that a crown fuel bulk density of  $6.8\text{ kg}\cdot\text{m}^{-3}$  was sufficient to successfully initiate a crown fire under the current experimental conditions, which included experiments with mean wind speeds ranging from  $0$  to  $1.8\text{ m}\cdot\text{s}^{-1}$ . Although this crown bulk density is higher than typical values measured in the field, live foliage and fine fuels are generally present in the lower portion of the canopy, and thus the crown bulk density tends to be higher in these regions as compared to the average crown bulk density. It was observed that the smoke from the surface fire easily passed through the crown fuel. This suggests that convective heating may be an effective heat transfer mechanism between the hot gases and the solid fuel. Lower crown fuel bulk densities resulted in successful ignition of the crown fuel at lower wind speeds, while much higher bulk densities precluded crown fire initiation. Thus, a crown fuel bulk density of  $6.8\text{ kg}\cdot\text{m}^{-3}$  was selected for the current laboratory-scale experiments.

In addition to the crown fuel bulk density, mean velocity of wind influences the extent to which convective heating of the crown fuel matrix occurs. Because the hot smoke movement is important for convective energy transfer, as described earlier, Froude number ( $Fr$ ) was used to characterize the surface fire in this study. Froude number represents a ratio of inertial to gravitational forces and is defined as  $Fr = U^2/gH$ , where  $U$  is wind speed,  $g$  is gravitational acceleration, and  $H$  is flame height. In southern California, prescribed burns are generally performed in spring to early summer with marginal burning conditions (Weise et al., 2005). The measured wind speeds at an elevation of  $6.1\text{ m}$  during prescription burning are typically less than  $5.5\text{ m/s}$ . With the wind reduction factor of  $0.6$  accounting for the influence of stand structure and canopy on wind (Rothermel, 1983), the  $6.1\text{ m}$  measured winds are reduced to mid-flame wind speeds of less than  $3.3\text{ m/s}$ . Thus, the Froude numbers in the field are in the range of  $0\text{--}1.1$  based on an estimated flame height of  $1.0\text{ m}$ . Accordingly, mean wind speed of  $1.5$  and  $1.8\text{ m/s}$  which result in the Froude numbers of approximately  $0.6$  and  $1.1$ , respectively, were selected for a detailed investigation. They were generated by three fans each with a diameter of  $48\text{ cm}$ , placed adjacent to each other to cover a  $144\text{ cm}$  wide and  $48\text{ cm}$  tall region, as shown in Figure 1b. The distance between the fans and the location of the crown fuel matrix was  $2.75\text{ m}$ . The wind velocity profiles in the direction of wind for low and high wind speed are shown in Figure 1c and 1d, respectively. Initial wind velocity of  $1.9\text{ m}\cdot\text{s}^{-1}$  averaged over time in a vertical plane perpendicular to the wind direction at the ignition zone decreased to  $1.5\text{ m}\cdot\text{s}^{-1}$  (low wind speed), where the crown fuel matrix began ( $2.75\text{ m}$  downstream). Velocity further decreased to  $1.2\text{ m}\cdot\text{s}^{-1}$  at the trailing edge of the surface fuel bed. For an initial wind velocity of  $2.2\text{ m}\cdot\text{s}^{-1}$ , the corresponding downstream wind velocities were  $1.8\text{ m}\cdot\text{s}^{-1}$  and  $1.6\text{ m}\cdot\text{s}^{-1}$ . In the rest of what follows, the mean wind speeds ( $1.5$  or  $1.8\text{ m}\cdot\text{s}^{-1}$ ) at the location of the crown fuel matrix are used. The variations of wind velocity with height were moderate. It was relatively uniform between  $0.1$  and  $0.4\text{ m}$  with the variation about  $6\%$ . The wind velocities started to decrease notably above  $0.4\text{ m}$ . The variations were found to be less than  $15\%$  at  $0.6\text{ m}$ . Because of the expected average surface flame height of  $0.3\text{--}0.4\text{ m}$ , this velocity profile was deemed to be adequate for this study. It was noted that the variations of wind speed along the width of surface fuel bed had a fair uncertainty, which is common for the configuration without lateral walls present.

The velocity fluctuation was 12%, which is high due to the lack of diffuser (i.e., screens and honeycomb).

The effects of varying crown base height and wind speed were investigated. The experiments were conducted with:

1. crown base heights of 0.2, 0.3, and 0.4 m under no-wind conditions, and
2. mean wind speed of 0, 1.5, and  $1.8 \text{ m} \cdot \text{s}^{-1}$  with a fixed crown base height of 0.2 m.

A completely randomized treatment design was used to ensure that the experimental order did not influence the results of any other tests that occurred closely together in time. Each experiment was repeated three times for the same nominal values of the controlling variables to eliminate effects of small changes in experimental conditions. The experimental results show the average value over three repetitions.

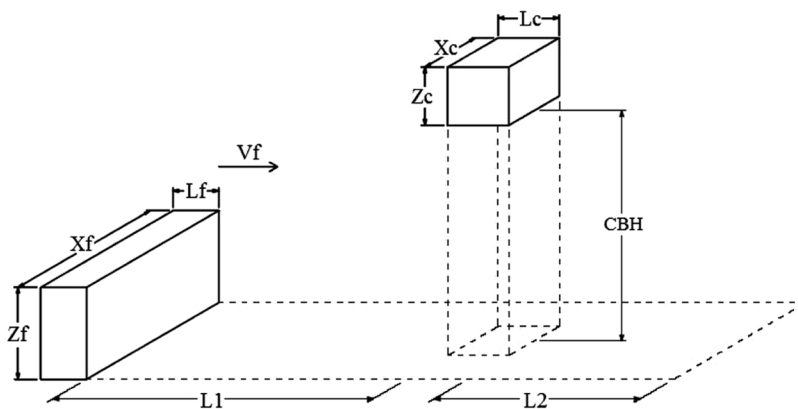
Fuel moisture of the excelsior and the chamise were not controlled. Excelsior is comprised of dead wood and its moisture content will equilibrate with ambient temperature and relative humidity given sufficient time and steady conditions (Nelson, 2001). The moisture content of excelsior can be estimated using equilibrium moisture content (EMC) (Simpson, 1998) based on the average ambient conditions (ambient temperature, 300 K; relative humidity, 33%) during the course of the experiments. However, chamise is a living plant that actively regulates and conserves water (Weise et al., 1996), and so the moisture content was measured a few minutes prior to each experiment using an Arizona Instruments Computrac 1000 moisture analyzer. The average dry-basis moisture content of the chamise needles and fine branches was approximately  $84\% \pm 5\%$  (for all experiments). The temperatures of the crown fuel (solid) and hot gases from the surface fire were measured at the midpoint of the bottom surface of the crown fuel by a set of 0.51 mm diameter (24 gauge) type K (chromel-alumel) thermocouples that have a response time of 0.86 s. One thermocouple was inserted into a 2 mm-diameter hole made in the woody chamise stem to approximate the crown fuel solid surface temperature as shown in Figure 1e. Radiation correction was applied to the measured hot gas temperatures (Cox & Chitty, 1985), and the temperature was corrected approximately 85 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. The total time from ignition to completion of burning ranged from 60 to 120 seconds. The rate of spread of the surface fire was extracted from video images when the fire front had traversed approximately 0.4 m from the ignition line.

## MODEL DESCRIPTION

To investigate the important factors that control crown fire initiation, a simple model based on heat transfer theory was developed to predict crown fire initiation above a prescribed surface fire. Several simplifying assumptions were invoked to make the model tractable while retaining the essential energy transfer mechanisms. The surface fire was treated as non-oscillating, and the flame height and its surface temperature were assumed uniform. With this assumption, the unsteady, fluid dynamics during the crown fire initiation process cannot be captured. This is likely

to cause an error in the prediction for situations in which these unsteady effects prevent crown fuel ignition even though the crown fuel temperature is sufficiently high. Despite this limitation, the main heat transfer mechanisms can be quantitatively evaluated with this assumption. The temperature of hot air was assumed to decrease with vertical height for the surface fire via a plume model described later in this section. A simple model for convective heat transfer was implemented by assuming that the crown fuel was fairly porous and heat can transfer from flame to the inside of crown fuel by convection, while heat transfer from the crown fuel occurs by radiation and convection to the surroundings. Heat conduction within the solid fuel matrix was modeled using Fourier law. Although conduction heat transfer was assumed to be an insignificant component of overall heat transfer, it was included for the sake of completeness. For modeling radiation, the system was viewed as a three-surface enclosure that was composed of surface fire, crown fuel, and surrounding ambient medium; only the outer surface of the crown fuel was exposed to radiation heat flux from the surface fire. For the present crown fuel setup, the mean free path of radiation was about 4.3 cm estimated as  $4/\beta\sigma_s$ , where  $\beta$  is the packing ratio and  $\sigma_s$  is the ratio of surface area to volume of the solid phase (Zhou et al., 2005). Considering attenuation of radiation in porous media and the simplification of model, only the computational cells at the boundary were assumed to absorb radiation from the surface fire.

The input variables for the model are flame size, flame temperature, crown fuel size, crown fuel bulk density, crown base height, crown fuel particle characteristics (that is, size and moisture content), and initial distance between flame front and crown fuel, as shown in Figure 2. Thus, the surface fire characteristics are prescribed either empirically or by using the fire propagation model of Koo et al. (2005). Koo et al.'s model is a simple physical model for one-dimensional steady-state contiguous spread of a line fire on a thermally-thin, uniform porous fuel bed. It is based on energy conservation and detailed heat transfer mechanisms. A solution for the fire spread rate is found as an eigenvalue of an appropriate boundary-value problem



**Figure 2** A schematic representation of surface to crown fire transition model. The surface fire moves from left to right.

through a standard fourth order Runge-Kutta method. The input parameters of Koo et al.'s model are fuel characteristics, wind speed, slope conditions, and flame length (or height), all obtained experimentally. Other models may be used such as BEHAVE (Andrews, 1986) and FARSITE (Finney, 1998), which predict the spread rate based on empirical data. However, Koo et al.'s model is readily adaptable for the diverse fuel configurations. It is also an improvement over BEHAVE and has the potential to be used as an operational model.

The model solves the time-dependent energy conservation equation for the solid fuel within the crown fuel matrix. Unlike equations in the gas phase, the governing equations are simpler, as the solid fuel mass is assumed stationary. Thus, phenomena such as transport of burning embers, collapse of the solid fuel matrix, etc., are disallowed in this formulation. The surface and inner temperatures of the crown fuel will increase with an external heat flux. Heat transfer and pyrolysis inside the wood material was modeled using the model of Atreya (1984). When the temperature is sufficiently high, incoming heat will be invested in evaporating water, and the pyrolysis process begins to decompose cellulose (foliage) and wood into combustible gases. Subsequently, the crown fuel may end up igniting when the temperature reaches an appropriate ignition temperature (Albini, 1996; Babrauskas, 2002; de Mestre et al., 1989), at which the fuel volatiles released by the fuel particles begin to burn. Ignition temperature is the critical fuel temperature at which flaming combustion is initiated (Saito, 2001; Williams, 1982). While related work suggests a range in ignition temperature for live foliage samples (Babrauskas, 2002; Engstrom et al., 2004), the most commonly reported ignition temperature is 523 K, which is the best estimate of the ignition temperature, provided that heating conditions are just barely enough for ignition, irrespective of type of heating (Babrauskas, 2002). Although the literature has shown that both the minimum pyrolysis rate and the minimum surface temperature can be used as criteria for ignition, the surface temperature criterion is much more convenient from a practical point of view (Liodakis et al., 2002). Currently, no ignition model is implemented, and thus transition to crown fire is presumed to have occurred when the crown fuel temperature reaches ignition temperature (523 K). The governing equation for energy within the crown fuel is given by

$$\frac{\partial T}{\partial t} = q_{conv} + q_{cond} + \frac{\partial \rho_w}{\partial t} [\Delta H_{py} - C_1(T - T_0)] + \frac{\partial \rho_m}{\partial t} [\Delta H_{ev} - C_2(T - T_0)] \quad (1)$$

where  $q_{conv}$  and  $q_{cond}$  denote convective and conductive heat transfer rate ( $\text{W} \cdot \text{m}^{-2}$ ), respectively. The quantities  $\rho_w$  and  $\rho_m$  are the bulk density of wood and moisture ( $\text{kg} \cdot \text{m}^{-3}$ ). The quantities  $\Delta H_{py}$  and  $\Delta H_{ev}$  are heats of pyrolysis and water evaporation ( $\text{kJ} \cdot \text{kg}^{-1}$ ). Coefficients  $C_1$  and  $C_2$  are defined as (Ritchie et al., 1997):

$$C_1 = \frac{\rho_{wo} \overline{c_{p,wo}} - \rho_{wf} \overline{c_{p,c}}}{\rho_{wo} - \rho_c} - \overline{c_{p,g}} \quad \text{and} \quad C_2 = \overline{c_{p,m}} - \overline{c_{p,g}} \quad (2)$$

where  $\rho_{wo}$  and  $\rho_c$  are the densities of dry virgin wood and char. The specific heat ( $\text{kJ} \cdot \text{kg}^{-1} \text{C}^{-1}$ ) of wood ( $c_{p,wo}$ ), char ( $c_{p,c}$ ), and volatile gases ( $c_{p,g}$ ) are

assumed to be that of Douglas fir (*Pseudotsuga menziesii*) and vary over the range of temperature as (Fredlund, 1993; Parker, 1989)

$$c_{p,wo} = 0.10 + 0.0037 \cdot T \quad (3)$$

$$c_{p,c} = -1.47 + 1.14 \times 10^{-2} \cdot T - 1.65 \times 10^{-5} \cdot T^2 + 1.09 \times 10^{-8} \cdot T^3 - 2.66 \times 10^{-12} \cdot T^4 \quad (4)$$

$$c_{p,g} = 5.24 \times 10^{-1} + 1.84 \times 10^{-3} \cdot T - 3.76 \times 10^{-7} \cdot T^2 \quad (5)$$

The thermophysical properties of wood during charring can be calculated from (Ritchie et al., 1997)

$$\overline{\rho c_p} = \rho_a c_{p,wo} + \rho_c c_{p,c} + \rho_m c_{p,m} \quad (6)$$

The over-bar denotes evaluation at the average of instantaneous temperature  $T$  and initial temperature  $T_o$ . The density of active wood ( $\rho_a$ ) is

$$\rho_a = \left( \frac{\rho_w - \rho_c}{\rho_{w,o} - \rho_c} \right) \rho_{w,o} \quad (7)$$

The pyrolysis rate is modeled as a first-order Arrhenius reaction as

$$\frac{\partial \rho_w}{\partial t} = -k_A \rho_a \exp\left(\frac{-E_a}{RT}\right) \quad (8)$$

where the kinetics parameters are taken from the model of (Porterie et al., 2000) for pine needles in which the pre-exponential factor ( $k_a$ ) is  $-3.63 \times 10^4 \text{ s}^{-1}$ , and the activation energy ( $E_a$ ) is  $6.05 \times 10^4 \text{ J} \cdot \text{mole}^{-1}$ . It was reported that the difference in species of leaves shows a small effect on the kinetic parameters (Smith et al., 2004; Susott, 1982). This issue needs further investigation. The evaporation rate is taken from the model of Porterie et al. (2000) for pine needles as

$$\frac{\partial \rho_m}{\partial t} = 3.63 \times 10^4 \rho_m \exp(-5800/T) \quad (9)$$

Because only the outer surface of crown fuel is exposed to radiation from the surface fire, an additional heat transfer term  $q_{rad}$  is added to the right-hand side of the energy Eq. (1) for computational cells that include a boundary surface.

The system is viewed as a three-surface enclosure that is composed of surface fire, crown fuel and surroundings. By assuming the flame temperature is constant, the net rate of radiation heat transfer between surface fire and crown fuel can be obtained from

$$q_{rad} = \frac{E_{b,fuel} - J_{fuel}}{(1 - \epsilon_{fuel}) / \epsilon_{fuel} A_{fuel}} \quad (10)$$

where  $E_{b,fuel}$ ,  $J_{fuel}$ ,  $\varepsilon_{fuel}$  and  $A_{fuel}$  are emissive power, radiosity ( $\text{W} \cdot \text{m}^{-2}$ ), emissivity and surface area per unit volume of crown fuel, respectively. In this study, the radiation from surface fire was assumed to be a surface phenomenon. Because thermal radiation generally arises from the whole volume of the flame and not just from its surface, the surface emissivity depends on the scale of the fire and is in the range of 0.20 to 1.00. For high intensity fire experiments with sufficiently thick flames of 2 to 3 m, the surface emissivity can be 0.90 to 1.00 (Sullivan et al., 2003) as it radiates as a black body. However, for the current laboratory scale experiment with approximately 0.10 m thick flame, the surface emissivity of surface fire was assumed to be 0.20 since the flame thickness is relatively small. The emissivity of the chamise was assumed to be 0.65 for shrub fuel (Kremens & Faulring, 2003). By approximating the surrounding as a blackbody of known temperature ( $J_{sur} = E_{b,sur}$ ),  $J_{fuel}$  may be obtained from fuel surface and fire surface by

$$\frac{E_{b,fuel} - J_{fuel}}{(1 - \varepsilon_{fuel})/\varepsilon_{fuel}A_{fuel}} = \frac{J_{fuel} - J_{fire}}{1/A_{fuel}F_{fuel-fire}} + \frac{J_{fuel} - J_{sur}}{1/A_{fuel}F_{fuel-sur}} \quad (11)$$

$$\frac{E_{b,fire} - J_{fire}}{(1 - \varepsilon_{fire})/\varepsilon_{fire}A_{fire}} = \frac{J_{fire} - J_{fuel}}{1/A_{fire}F_{fire-fuel}} + \frac{J_{fire} - J_{sur}}{1/A_{fire}F_{fire-sur}} \quad (12)$$

The view factor  $F_{ij}$  which is the fraction of the radiation leaving surface  $i$  that is intercepted by surface  $j$ , can be determined by

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \theta_i \cos \theta_j}{\pi R^2} dA_i dA_j \quad (13)$$

where  $A_i$  and  $A_j$  are surface area per unit volume of surfaces  $i$  and  $j$ ,  $R$  is distance between surface  $i$  and  $j$ , and  $\theta_i$  and  $\theta_j$  are the polar angles of line connecting surfaces  $A_i$  and  $A_j$ . The rate of convection and conduction heat transfer can be calculated from

$$q_{conv} = hA(T_{air} - T_{fuel}) \quad \text{and} \quad q_{cond} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (14)$$

where  $k$ ,  $h$ ,  $A$ ,  $T_{air}$ , and  $T_{fuel}$  are thermal conductivity, heat transfer coefficient, surface area per unit volume of each finite difference cell, temperature of air above the flame, and temperature of crown fuel, respectively. The heat transfer coefficient used is that for a bank of tubes, which can be deduced from the Nusselt number (Nu) (Incropera & DeWitt, 2002), which is estimated as (Cruz et al., 2006b; Mendes-Lopes et al., 2002)

$$h = \frac{\text{Nu} \cdot k_a}{d}, \quad \text{Nu} = 0.1417 \cdot \text{Re}^{0.6053} \quad (15)$$

where  $k_a$  is thermal conductivity of hot air,  $d$  is diameter of fuel particle (leaf and branch), and Re is the Reynolds number. The centerline velocity and temperature

of air above the flame can be estimated by a plume model (Yuan & Cox, 1996):

$$\frac{v_m}{Q_l^{1/3}} = A_m \left( \frac{z}{Q_l^{2/3}} \right)^n \quad \text{and} \quad \Delta T_m = B_m \left( \frac{z}{Q_l^{2/3}} \right)^{2n-1} \quad (16)$$

where  $v_m$ ,  $Q_l$ ,  $z$ , and  $\Delta T_m$  are centerline velocity of hot air, heat release from surface fire, height above the surface fire, and temperature rise above the ambient of hot air, respectively. Empirical constants  $A_m$ ,  $B_m$ , and  $n$  are evaluated from the experiments. The values for  $A_m$ ,  $B_m$ , and  $n$  are 2.4, 728, and 0.5, respectively, for the continuous flame region, and are 3.8, 8.6, and 0.0, respectively, for the intermittent flame region. For wind-aided conditions, surface flame tilt angle ( $\theta_m$ ) is the result of the competition between buoyancy and wind. It can be prescribed either empirically or calculated by (Morandini et al., 2001):

$$\tan \theta_m = \frac{v_m}{U} \quad (17)$$

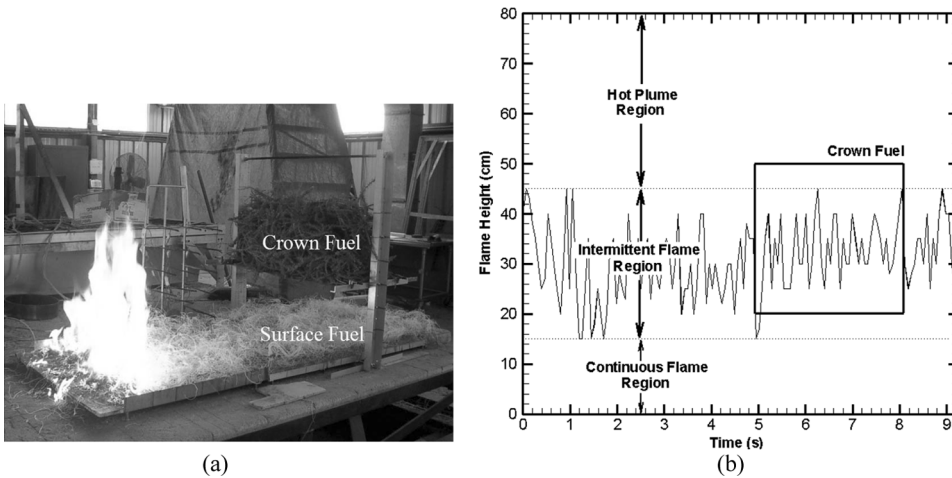
where  $U$  represents the wind speed. Both  $v_m$  and  $U$  are at mid-flame height. Other models to approximate the tilt angle may be applied corresponding to the fuel configurations (see, for example, Albini, 1981; Nelson & Adkins, 1986; Putnam, 1965; Weise & Biging, 1996).

The crown fuel was discretized into equi-spaced volumes, and the energy equation in discretized form (using second-order, central differencing) is obtained for all interior finite volumes and those exposed to the surface. The semi-discrete equations were then advanced in time using a standard Runge-Kutta method available in MATLAB<sup>®</sup>. A uniform temperature within the crown fuel was initiated as the ambient temperature. Radiative heat transfer to the crown fuel was calculated by assuming the surface fire was a hot surface with a constant temperature. Convective heat transfer was included at all nodes that are above the surface fire by assuming that the temperature and centerline velocity of the hot air over the flame decays with height via Eq. (16). Computations were carried out until the flame front reaches the edge of the domain. A grid independence study revealed that  $31 \times 31 \times 81$  uniformly spaced computational cells was sufficient to model the time-dependent energy equation over the  $0.30 \text{ m} \times 0.30 \text{ m} \times 0.80 \text{ m}$  volume of crown fuel.

## RESULTS AND DISCUSSION

### Experimental Results

The effect of varying crown base height and wind speed was investigated experimentally as described previously. Under no wind condition, the surface fire spread as shown in Figure 3a at an average rate of spread ( $ROS$ ) of  $1.9 \text{ cm} \cdot \text{s}^{-1}$  with a standard deviation of  $0.1 \text{ cm} \cdot \text{s}^{-1}$ . The average visible flame height was  $0.30 \text{ m}$  with a standard deviation of  $0.02 \text{ m}$ , obtained by processing data captured by a camcorder. The minimum and maximum flame heights were  $0.15 \text{ m}$  and  $0.45 \text{ m}$ , respectively. Thus, the crown fuel base was located in the intermittent flame region, as shown in Figure 3b.



**Figure 3** Illustration of (a) spreading of surface fire, and (b) flame height under no wind condition with the crown base height of 0.20 m.

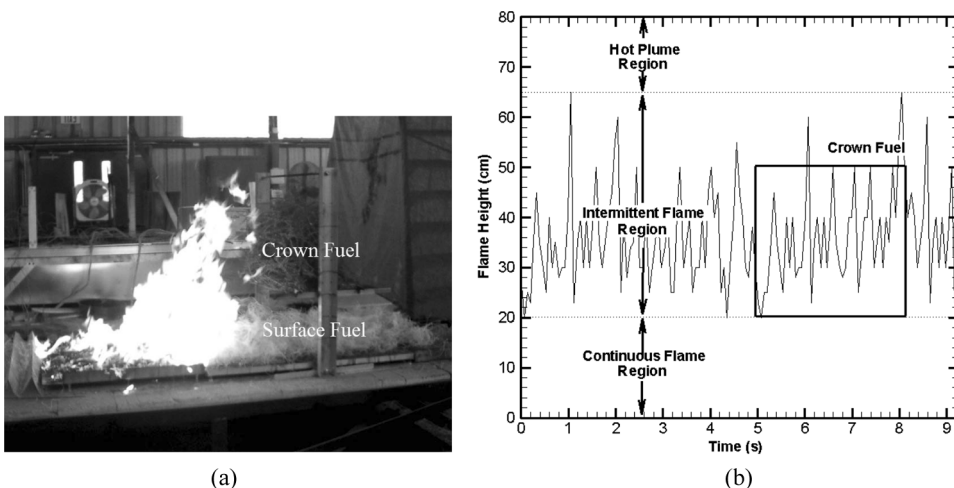
Table 1 shows the experimental results on crown fire transitions at different crown base heights of 0.20, 0.30, and 0.40 m under no wind condition. For the crown base height of 0.40 m, the temperature of hot combustion products originating from the surface fire decayed to 407 K (were shown to be repeatable to  $\pm 69$  K) at the bottom of crown fuel. This is the average temperature at the crown fuel base, noted as  $T_{a,c}$ . This hot air supplied convective heating to the crown fuel and raised its temperature to 357 K (shown to be repeatable to  $\pm 11$  K), which was insufficient for ignition. When the crown base height decreased to 0.30 m, the vertical distance decreased so that less cool air is entrained into the hot gas that originated from the surface fire. Thus, the average temperature at the crown fuel base ( $T_{a,c}$ ) increased to 564 K (shown to be repeatable to  $\pm 75$  K). This hot air supplied convective heating to the crown fuel, raising its temperature so that it exceeded ignition temperature of 523 K (Babrauskas, 2002). Ignition temperature is the critical fuel temperature at which flaming combustion is initiated (Saito, 2001; Williams, 1982). While related work suggests a range in ignition temperature for live foliage samples between 500–600 K (Babrauskas, 2002; Engstrom et al., 2004), the most commonly reported ignition temperature is 523 K, which is the best estimate of the ignition

**Table 1** Experimental results on crown fire transitions at different crown base heights (CBH)

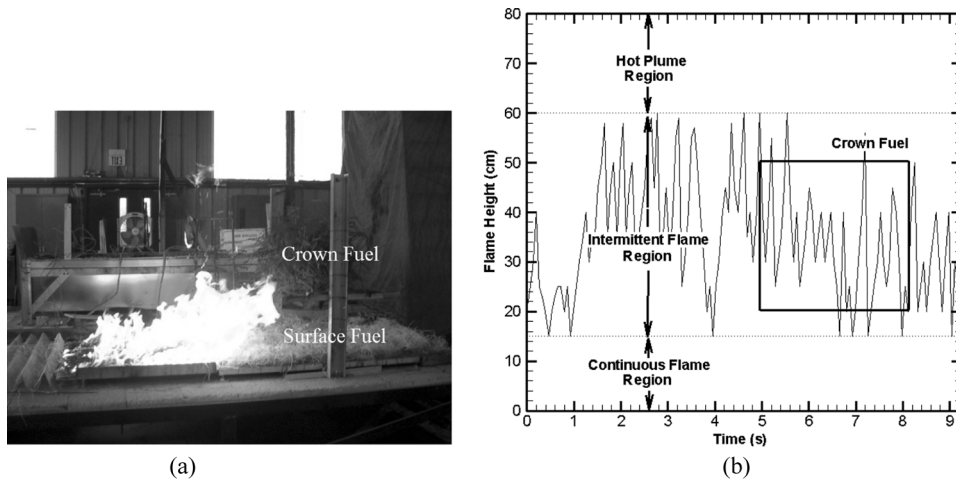
| CBH<br>(m) | Wind<br>( $\text{m} \cdot \text{s}^{-1}$ ) | $T_a$<br>(K) | $RH$<br>(%) | Flame height (m) |      |      | Flame<br>thickness (m) | Flame tilt<br>angle ( $^\circ$ ) | $ROS$<br>( $\text{cm} \cdot \text{s}^{-1}$ ) | $T_{a,c}$<br>(K) | Ignition<br>success |
|------------|--------------------------------------------|--------------|-------------|------------------|------|------|------------------------|----------------------------------|----------------------------------------------|------------------|---------------------|
|            |                                            |              |             | Min.             | Avg. | Max. |                        |                                  |                                              |                  |                     |
| 0.20       | 0                                          | $300 \pm 5$  | $36 \pm 3$  | 0.15             | 0.30 | 0.45 | $0.10 \pm 0.05$        | 0                                | $1.9 \pm 0.1$                                | $586 \pm 62$     | Yes                 |
| 0.30       | 0                                          | $298 \pm 5$  | $38 \pm 3$  | 0.15             | 0.30 | 0.45 | $0.10 \pm 0.05$        | 0                                | $1.9 \pm 0.1$                                | $564 \pm 75$     | Yes                 |
| 0.40       | 0                                          | $298 \pm 5$  | $38 \pm 3$  | 0.15             | 0.30 | 0.45 | $0.10 \pm 0.05$        | 0                                | $1.9 \pm 0.1$                                | $407 \pm 69$     | No                  |

temperature, provided that heating conditions are just barely enough for ignition, irrespective of type of heating (Babrauskas, 2002). A part of the crown fuel ignited and burned in smoldering mode and then transitioned to flaming combustion. The crown fire was successfully initiated. A similar process was observed when the crown base height was decreased to 0.20 m. The average temperature at the crown fuel base increased even further to 586 K (were shown to be repeatable to  $\pm 62$  K). Convective heating of the crown fuel increased so the crown fuel ignited successfully. Under the same nominal experimental conditions, repeated burning tests showed that the crown fire was initiated for crown base heights of 0.20 and 0.30 m, but no crown fire was observed for a crown base height of 0.40 m. The temperature of hot gas and crown fuel were observed to increase when the crown base height was decreased. Therefore, the effect of varying crown base height was easy to interpret with lower height enhancing crown fire initiation.

A wind speed of  $1.5 \text{ m} \cdot \text{s}^{-1}$  caused the surface fire to tilt as shown in Figure 4a. It can be seen that the flame was still dominated by buoyancy ( $Fr = 0.6$ ) as the hot smoke rises almost vertically. In this case, wind accelerated the surface fire combustion rate so the average rate of spread increased to  $3.2 \text{ cm} \cdot \text{s}^{-1}$  with a standard deviation of  $0.3 \text{ cm} \cdot \text{s}^{-1}$ . The average visible flame height increased to 0.34 m with a standard deviation of 0.03 m. The minimum and maximum flame heights were 0.20 m and 0.65 m, respectively. Thus, the crown base of 0.20 m was situated within the continuous flame region of the surface fire, as shown in Figure 4b. When the wind speed increased to  $1.8 \text{ m} \cdot \text{s}^{-1}$ , the surface fire tilt angle increased, as shown in Figure 5a. In this case, it is clear that the flame was dominated by the wind ( $Fr = 1.1$ ). The hot smoke trajectory was significantly inclined toward the unburned fuel. The average rate of spread of surface fire increased to  $3.9 \text{ cm} \cdot \text{s}^{-1}$  with a standard deviation of  $0.2 \text{ cm} \cdot \text{s}^{-1}$ . However, the average visible flame height decreased to 0.32 m with a standard deviation of 0.03 m. The minimum and maximum flame height



**Figure 4** Illustration of (a) spreading of surface fire, and (b) flame height under wind speed  $1.5 \text{ m} \cdot \text{s}^{-1}$  with the crown base height of 0.20 m.



**Figure 5** Illustration of (a) spreading of surface fire, and (b) flame height under wind speed of  $1.8 \text{ m} \cdot \text{s}^{-1}$  with the crown base height of 0.20 m.

heights were 0.15 m and 0.60 m, respectively. Thus, the crown base of 0.20 m was situated within the intermittent flame region of the surface fire, as shown in Figure 5b.

Table 2 summarizes the experimental results on crown fire transitions at different wind speed of 0.0, 1.5, and  $1.8 \text{ m} \cdot \text{s}^{-1}$  with the crown base height fixed at 0.20 m. For a wind speed of  $1.5 \text{ m} \cdot \text{s}^{-1}$ , it can be seen that wind accelerated combustion rate, so the temperature of the hot gas at the bottom of crown fuel increased to 659 K (were shown to be repeatable to  $\pm 76 \text{ K}$ ), resulting in an increase in convective heating to the crown fuel. It is also noticed that the higher surface fire spread rate with wind reduced the residence time of convective heating. The residence time of convective heating refers to the time (in seconds) during which the temperatures of the hot gas from surface fire at a stationary point exceed 500 K. In this case, the residence time of convective heating is 9.0 s. This residence time of convective heating was sufficient so that the crown fire was successfully initiated. For a higher wind speed of  $1.8 \text{ m} \cdot \text{s}^{-1}$ , although the flame height was increased compared to the no wind situation, the residence time of convective heating decreased to 7.5 s, which was not sufficient for ignition. However, this residence time of convective heating is barely

**Table 2** Experimental results on crown fire transitions at different wind conditions

| CBH<br>(m) | Wind<br>( $\text{m} \cdot \text{s}^{-1}$ ) | $T_a$<br>(K) | $RH$<br>(%) | Flame height (m) |      |      | Flame<br>thickness (m) | Flame Tilt<br>angle ( $^\circ$ ) | $ROS$<br>( $\text{cm} \cdot \text{s}^{-1}$ ) | $T_{a,c}$<br>(K) | Ignition<br>success |
|------------|--------------------------------------------|--------------|-------------|------------------|------|------|------------------------|----------------------------------|----------------------------------------------|------------------|---------------------|
|            |                                            |              |             | Min.             | Avg. | Max. |                        |                                  |                                              |                  |                     |
| 0.20       | 0                                          | $300 \pm 5$  | $36 \pm 3$  | 0.15             | 0.30 | 0.45 | $0.10 \pm 0.05$        | 0                                | $1.9 \pm 0.1$                                | $586 \pm 62$     | Yes                 |
| 0.20       | $1.5 \pm 0.2$                              | $305 \pm 5$  | $35 \pm 3$  | 0.20             | 0.34 | 0.65 | $0.30 \pm 0.05$        | $38 \pm 15$                      | $3.2 \pm 0.3$                                | $659 \pm 76$     | Yes                 |
| 0.20       | $1.8 \pm 0.2$                              | $298 \pm 5$  | $37 \pm 3$  | 0.15             | 0.32 | 0.60 | $0.40 \pm 0.05$        | $51 \pm 15$                      | $3.9 \pm 0.2$                                | $623 \pm 69$     | No                  |

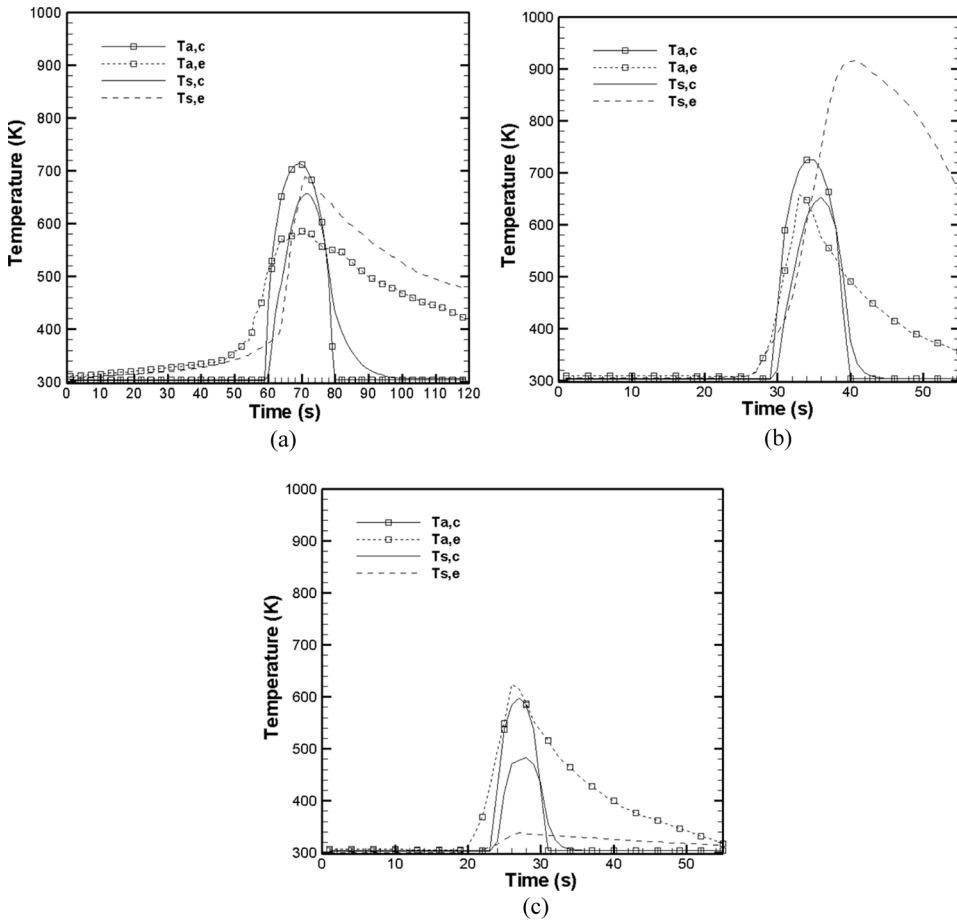
sufficient to ignite a portion of the crown fuel in a glowing mode. Nevertheless, it failed to transition to a visible flame because the wind flow induced a cooling effect on the crown fuel. Thus, after the surface fire passed the crown fuel, the crown fire was not initiated. In this case, it was noticed that the peak gas temperature was lower, compared with that under no wind conditions. The hot gas temperature in the region below the crown fuel matrix decreased to 623 K (shown to be repeatable to  $\pm 69$  K). The higher surface fire spread rate reduced the residence time of convective heating to 7.7 s, resulting in a decrease in convective heating. Therefore, it can be concluded that increasing wind speed decreases the propensity for crown fire initiation for the current experimental setup. However, we concede that different crown fuel arrangements may yield slightly different conclusions, as they might influence the energy transfer process.

### Model Results

The effect of varying crown base height and wind speed on energy absorbed by crown fuel was investigated using the simple model described previously. The crown base heights investigated were 0.20, 0.30, and 0.40 m, and the wind speeds were 0.0, 1.5, and  $1.8 \text{ m} \cdot \text{s}^{-1}$ . These values correspond to the laboratory experiments. For the successful ignition case, Figures 6a and 6b show a comparison of the experimental temperature measurements with numerical predictions for no wind condition and under a wind speed of  $1.5 \text{ m} \cdot \text{s}^{-1}$ , respectively. The crown base height was 0.20 m. At early times, the crown fuel temperature increased slowly by radiation before the flame reached the base of the crown (at  $t = 58$  and  $28$  s for Figures 6a and 6b, respectively), then it rose rapidly to a maximum due to additional convective heating from the surface fire. Finally, after the flame passed the base of the crown (at  $t = 80$  and  $40$  s for Figure 6a and 6b, respectively), convective cooling overcame the incoming heat transfer, and the temperature began to decrease. Figures 6a and 6b show that the values predicted by the model agreed with the measurement until the temperature of crown fuel reached 523 K; after that, the measured values were much higher than the predicted values. This likely occurred because the crown fuel starts to ignite when its temperature reached 523 K, so the actual temperature of crown fuel rose rapidly due to heat of combustion, while the calculated temperature continues to rise due to energy transfer from the surface fire. Consequently, the heat released from the crown fuel burning resulted in the higher air temperature. However, because burning effects were not considered in this model, a distinct difference was observed when the crown fire begins to initiate.

For the unsuccessful case, Figure 6c shows a comparison of the experimental temperature measurements with numerical predictions for a wind speed of  $1.8 \text{ m} \cdot \text{s}^{-1}$ . The peak air temperature at the crown base was reduced from 728 K to 598 K, which directly affected the convective heating of crown fuel. Because of a greater cooling effect induced by higher wind velocity, the predicted crown temperature did not exceed the assumed ignition temperature (523 K), and the crown fire was not initiated. This agreed well with the experimental result. Overall, model predictions matched the experimental results well in terms of the overall trend.

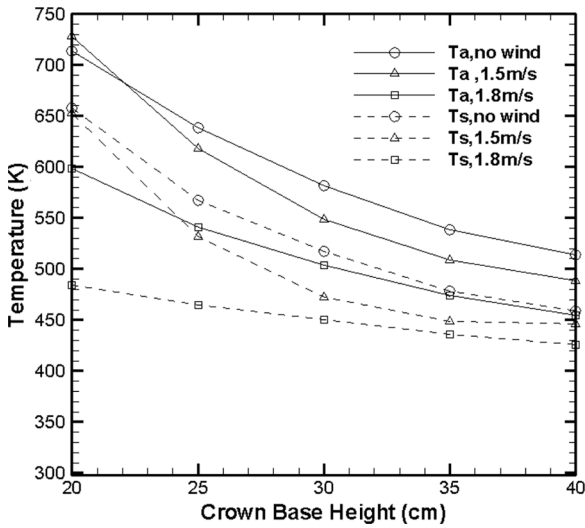
Figure 7 shows the predicted maximum air and crown fuel temperatures at the crown base for different crown base heights and wind speeds. In examining the effect



**Figure 6** Time evolution of calculated air and crown fuel temperature from the simple model and experimental temperature of air and crown fuel at the crown base for (a) no wind, (b) wind speed of  $1.5 \text{ m} \cdot \text{s}^{-1}$ , and (c) wind speed of  $1.8 \text{ m} \cdot \text{s}^{-1}$  with the crown base height of  $0.20 \text{ m}$ .  $T_{a,c}$  and  $T_{s,c}$  denote the computed air and solid crown fuel temperature, and  $T_{a,e}$  and  $T_{s,e}$  denote the corresponding experimentally measured values.

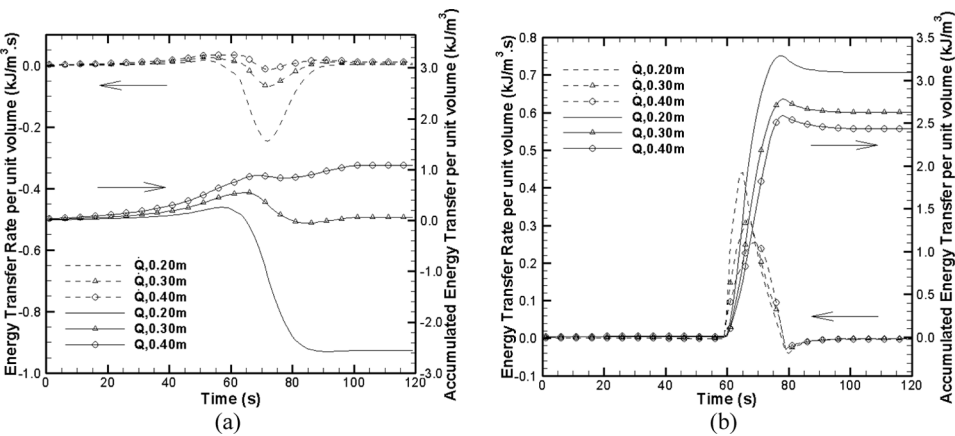
of varying crown base height, it is clear that the maximum hot gas and crown fuel temperatures at the crown base decreased when the crown base height increased from  $0.20$  to  $0.40 \text{ m}$ . The model also predicts that the maximum temperatures of hot gas and crown fuel decreased when wind speed increased from  $0.0$  to  $1.8 \text{ m} \cdot \text{s}^{-1}$ . However, it was noticed that wind might increase the maximum hot gas temperature. This appears in the event when the wind speed increases from  $0.0$  to  $1.5 \text{ m} \cdot \text{s}^{-1}$  with the crown base height of  $0.20 \text{ m}$ . This is because wind increases the flame height and causes the continuous flame region to reach the crown base.

The model may be used to better understand these overall effects by examining contributions to heating/cooling via the different modes of energy exchange. Thus, for example, the effects of varying crown base height and wind speed on the energy

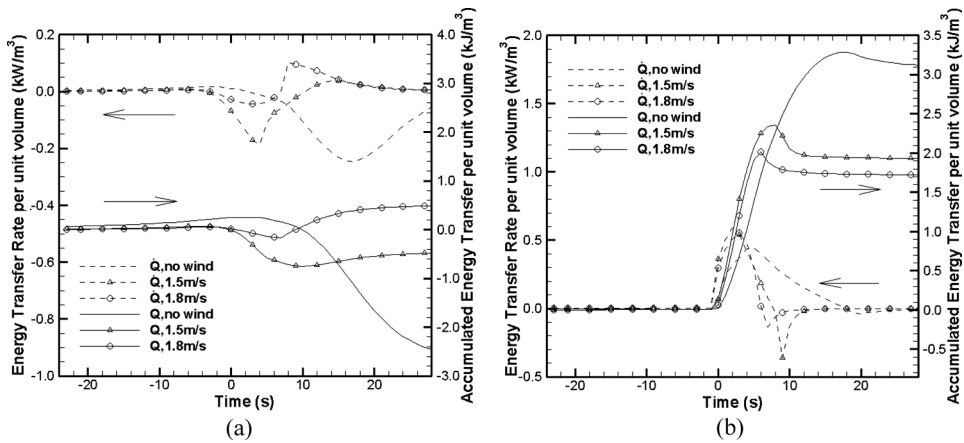


**Figure 7** The maximum temperature of air and crown fuel at the crown base calculated from the semi-empirical model with different crown base heights and wind speeds.

transfer to the crown fuel are shown in Figures 8 and 9. Figures 8a and 8b show time evolution of convective and radiative energy transfer rate per unit volume and accumulated convective energy per unit volume absorbed by solid particle located at the bottom of the crown fuel under no wind condition for three crown base heights of 0.20, 0.30, and 0.40 m. The accumulated value was computed by integrating their instantaneous rates per unit volume over time. Initially, the crown fuel absorbs radiative energy slowly before the flame reaches the base of the crown. At this time (around  $t = 60$  s), the crown fuel is heated by convection, so its temperature



**Figure 8** Time evolution of (a) radiative and (b) convective energy per unit volume absorbed by solid particle located at the bottom of the crown fuel calculated from the semi-empirical model under no wind condition with different crown base height of 0.20, 0.30, and 0.40 m.



**Figure 9** Time evolution of (a) radiative and (b) convective energy per unit volume absorbed by solid particle located at the bottom of the crown fuel calculated from the semi-empirical model with crown base height of 0.20 m at different wind speed of 0, 1.5, and 1.8 m/s (time = 0 when the flame reaches the crown base).

rose rapidly and it started to lose heat through radiation. Because the radiative energy loss overwhelmed the convective energy incoming from the flame at  $t = 70$  s, the crown fuel temperature started to decrease. After the flame passed the base of the crown at  $t = 80$  s, the crown fuel started to lose heat through convection, and its temperature continues to decrease. It was observed that the convective energy absorbed by the crown fuel was much higher than radiative energy; thus, the major heat transfer mechanism was convection. With varying crown base height, it can be seen that the accumulated radiative energy absorbed by the crown fuel increased from 0.26 to  $0.89 \text{ kJ} \cdot \text{m}^{-3}$  when the crown base height increased from 0.20 to 0.40 m, while the accumulated convective energy absorbed by the crown fuel decreased from 3.29 to  $2.59 \text{ kJ} \cdot \text{m}^{-3}$ . Energy transferred by radiation increased because of the larger area of flame available for radiation exchange between the surface fire and crown fuel. The convective energy decreased because the temperature of hot gas at crown base decreased with increasing crown base height. Thus, it can be concluded that lower crown base height enhanced the propensity for crown fire initiation by increasing the convective energy transfer to the crown fuel.

Figures 9a and 9b show time evolution of convective and radiative energy transfer rate per unit volume and accumulated convective energy per unit volume absorbed by solid particles located at the bottom of the crown fuel with crown base height of 0.20 m for different wind speeds of 0.0, 1.5, and  $1.8 \text{ m} \cdot \text{s}^{-1}$ . It was noticed that wind increased the convective transfer rate although the hot gas temperature at the crown base decreased. This is because wind accelerated hot gas velocity, which increased the heat transfer coefficient directly via Eq. (15). The convective transfer rate increased from  $0.44$  to  $0.59 \text{ kJ} \cdot \text{m}^{-3} \cdot \text{s}$  when the wind speed increased from 0 to  $1.8 \text{ m} \cdot \text{s}^{-1}$ . However, it decreased the accumulated convective energy absorbed by the crown fuel. The accumulated convective energy absorbed decreased from  $3.29$  to  $2.02 \text{ kJ} \cdot \text{m}^{-3}$  when the wind speed increased from 0 to  $1.8 \text{ m} \cdot \text{s}^{-1}$ . This was

because wind accelerated the surface fire spread rate, which reduced the residence time of convective heating and thus reduced the net convective energy transfer to the crown fuel. Because the maximum temperature of crown fuel depends on the accumulated convective energy absorbed by the crown fuel, it can be concluded that higher wind speed prevented crown fire initiation by reducing the net convective energy transfer to the crown fuel. However, this conclusion may be different in the field where a horizontal distribution of crown fuel is not uniform. Wind may force the hot gas to flow through a particular path and extend the residence time of convective heating. The present model is unable to capture this fluid dynamic effect. Thus, although the present model and experimental results are useful, it is clear that further detailed study on the effects of wind is still needed. Currently, a three-dimensional large eddy simulation (LES) methodology (Zhou et al., 2006) is under development to enable modeling of fire spread through a shrub crown fuel under varying ambient wind conditions.

## CONCLUSIONS

Crown fire initiation from surface fire was investigated through experiments and numerical modeling. The experiments modeled the situation in which crown fuels are segregated, as might be the case in chaparral stands in southern California as well as other shrub types around the world. Crown base heights ranged from 0.20 m to 0.40 m, and wind speeds ranged from 0.0 to  $1.8 \text{ m} \cdot \text{s}^{-1}$ . A simple model based on fundamental heat transfer theory was proposed to predict crown fire initiation. The predicted results for different wind speeds and crown base height were in good agreement with the experimental measurements. Because of its relative simplicity and inclusion of basic physics, it is anticipated that the model can be readily applied and/or modified to model diverse fuel configurations. Under the current experimental conditions, it was found that higher crown base height reduced the chance of crown fire initiation. Increasing crown base height decreased the temperature of hot gas that originated from the surface fire and thus reduced the heat transfer to the crown fuel. Increased wind speed also decreased the possibility of crown fire initiation, as it reduced the residence time of convective heating and thus decreased the net energy transfer to the crown fuel. It is noted that the findings are based on a limited set of experimental conditions and, correspondingly, a limited set of computational results. Thus, the results represent a first step in better understanding the impacts of crown base height and wind on transition of a surface fire to a crown fire in shrublands.

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