CSIRO PUBLISHING

International Journal of Wildland Fire **2014**, *23*, 451–462
http://dx.doi.org/10.1071/WF12118

Experimental modelling of crown fire initiation in open and closed shrubland systems

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Abstract. The transition of surface fire to live shrub crown fuels was studied through a simplified laboratory experiment using an open-topped wind tunnel. Respective surface and crown fuels used were excelsior (shredded *Populus tremuloides* wood) and live chamise (*Adenostoma fasciculatum*, including branches and foliage). A high crown fuel bulk density of 6.8 kg m^{-3} with a low crown fuel base height of 0.20 m was selected to ensure successful crown fire initiation. Diagnostics included flame height and surface fire evolution. Experimental results were compared with similar experiments performed in an open environment, in which the side walls of the wind tunnel were removed. The effect of varying wind speed in the range 0–1.8 m s^{-1}, representing a Froude number range of 0–1.1, on crown fire initiation was investigated. The suppression of lateral entrainment due to wind tunnel walls influenced surface fire behaviour. When wind speed increased from 1.5 to 1.8 m s^{-1}, the rate of spread of surface fire and surface fire depth increased from 5.5 to 12.0 cm s^{-1} and 0.61 to 1.02 m. As a result, the residence time of convective heating significantly increased from 16.0 to 24.0 s and the hot gas temperature at the crown base increased from 994 to 1141 K. The change in surface fire characteristics significantly affected the convective energy transfer process. Thus, the net energy transfer to the crown fuel increased so the propensity for crown fire initiation increased. In contrast, increasing wind speed decreased the tendency for crown fuel initiation in an open environment because of the cooling effect from fresh air entrainment via the lateral sides of surface fire.

Additional keywords: fire behaviour, fire prevention.

Received 17 July 2013, accepted 19 November 2013, published online 9 April 2014

Introduction

California is one of several Mediterranean-like areas in the world where long, hot and dry summers coupled with heat waves or high-velocity foehn-type winds (Miller and Schlegel 2006) often produce spectacular wildfires in the shrub vegetation complex known as chaparral (Keeley 2000). Urban growth has encroached upon the areas where chaparral vegetation has evolved in response to fire; destruction of urban areas by these wildfires has occurred since the 1930s. A variety of shrub species grow in chaparral and the relative abundance of the species within a stand are determined by several factors including the amount of available moisture and sun exposure, the reproductive strategy utilised by the species, soil type and depth, elevation and latitude. A common characteristic of chaparral is that fires spread in the canopy or crown (elevated living foliage and branches). Over 100 species of shrubs with evergreen foliage occur in chaparral, and chamise is the most widely distributed species with a range from Baja California to northern California; chamise is often the dominant species at lower elevations and on xeric sites (Keeley 2000).

The importance of wind for successful propagation of prescribed burns in shrubs is generally known from empirical studies (Bruner and Klebenow 1979; Green 1981; Van Wilgen *et al.* 1985; Martins Fernandes 2001) that have produced empirical guidelines for the use of fire in these systems. Recent experiments and modelling have begun to provide insight into importance of wind in the successful propagation of a flame through a shrub fuel bed (Weise *et al.* 2005; Zhou *et al.* 2005), but the conditions under which a propagating fire front in an elevated shrub canopy is established from a surface fire, are not well defined or modelled. Understanding the role of wind that determines the onset of shrub canopy crown fire will enhance the ability to use prescribed burning to provide desired ecological benefits while reducing the risk of wildfire.

There has been a strong research focus on crown fires in coniferous forests in Russia and North America because of the significant role that these stand-replacing wildfires play in the ecology of the boreal and northern temperate forests as well as the risk posed to commercial forest resources (Albini and Stocks 1986; Grishin and Perminov 1989; Butler *et al.* 2004; Alexander and Cruz 2006). Although crown fires occasionally occur in other coniferous forest types in the United States (Cooper 1960; Wade and Ward 1973) and fires in shrublands consume the crowns, less effort has been devoted to the physical modelling of fire in these fuel types.

Many experimental observations and calculations have shown that the possibility of sustaining a crown fire is enhanced as the wind speed is increased (Morvan 2007). It was reported that wind aids the successful spread of shrub canopy crown fire under marginal conditions (Weise *et al.* 2005). When wind is present, a surface fire may spread in the direction of the ambient flow ('heading fire'), against the flow ('backing fire'), or laterally across the flow ('flanking fire'). In the case of a heading fire, the surface fire will lean forward and get closer to unburned surface fuel ahead of the flame front under the influence of wind (Fons 1946). As a result, wind increases rate of spread, depth of combustion zone and intensity of surface fire (see Pitts 1991). The heat transfer and flow characteristics of a backing fire are not as well studied (Nelson 1980); however, it is well known that the surface fire intensity of a backing fire can be of the order of 10 to 20% of a heading fire under the same environmental conditions (Catchpole *et al.* 1992).

For transition from a surface fire to a crown fire, wind may enable a surface fire to ignite the crown fuel in the case of heading fire, because it increases the energy release rate from surface fire. Wind may also increase ignition potential as it maintains glowing sources (Bunting and Wright 1974; Countryman 1980) that occur from char combustion and release large amounts of energy within the crown fuel matrix.

Cruz *et al.* (2006) indicated that the depth of combustion zone is an important factor influencing crown fire initiation. If the surface fuel is highly flammable, the depth of surface fire burning zone increases significantly under the presence of wind. Thus, the potential of crown fire initiation increases. Many studies found the same trend that wind increases the likelihood of crowning due to increasing surface fire spread rate and intensity (Van Wagner 1977; Alexander 1988; Xanthopoulos 1990; Scott and Reinhardt 2001).

However, wind may decrease the possibility of crown fire initiation by decreasing the residence time of flame front because the spread rate of surface fire increases with increasing wind speed along the direction of fire propagation. Wind may prevent the ignition of crown fuel by diluting the combustible gas mixture (Bilbao *et al.* 2001) or even forcing the pyrolysis gases to escape from the crown fuel matrix. If the surface fuel is poorly flammable, wind may prevent crown fire initiation by tilting the hot plume arising from the surface fire (Cruz *et al.* 2006). Luke and McArthur (1978) reported a situation in Tasmania in 1967 in which very few crown fires occurred during a high-wind event (wind velocity = 22 m s^{-1}) and the observation that fires in the crowns were blown out by the strong winds at the top of the tree canopy. Plucinski (2003) postulated that wind (airflow through the canopy) extinguishes experimental flames in the shrub foliage quickly through heat loss.

Many studies found that wind is required for sustained flaming combustion of crown fire; however, it may not be essential for ignition (Grishin and Perminov 1989; Catchpole 2001; Plucinski 2003). Tachajapong *et al.* (2009) reported the results of the transition process from a surface fire to a crown fire in open-environment laboratory-scale experiments. In their work, a wind tunnel was not employed, instead the experimental platform was unconfined. Although their studies included effects of varying wind speed, crown base height and crown bulk density, only the relevant results of varying wind speed are used in the present discussion. They observed that increasing wind speed decreased the propensity for crown fire initiation in the open environment wind setup. A wind speed of 1.5 m s^{-1} caused the surface fire to tilt towards the unburned fuel. More energy could be transferred to the unburned surface fuel so the average rate of spread and visible flame height of surface fire increased. The crown fuel ignited successfully as the convective energy transfer to crown fuel was sufficient. When the wind speed increased to 1.8 m s^{-1}, the average rate of spread and the tilt angle of surface fire increased. However, the average visible flame height decreased as the surface fire was significantly inclined towards the unburned fuel. The peak hot gas temperature at the bottom of the crown fuel decreased so it failed to ignite the crown fuel.

The focus of the present paper is on the ignition of shrub canopy crown fuel. The effects of varying wind on shrub canopy crown fire initiation were investigated by utilising laboratory experiments.

Methods

Description of experimental setup

In this study, wind is an important factor that affects the convective and gravitational processes associated with hot gases arising from the surface fire. Thus, the experiments were designed to preserve Froude number similarity (Quintiere 1989) of surface fire, before ignition of crown fuel, as observed in field experiments. Froude number scaling was used to maintain the correct balance between convective and gravitational processes in the experiment. Froude number is defined as $Fr = U_{\mathrm{wind}}^2/gZ_f$, where U_{wind} is the mid-flame wind speed, g is the acceleration due to gravity, and Z_f is the flame height of the surface fire which refers to the average maximum vertical distance between flame tip and ground straight below it (Merrill and Alexander 1987). Generally, prescribed burns in southern California are conducted in spring to early summer with the 6.1-m elevation wind speed of less than 5.5 m s^{-1} (i.e. 3.3-m s^{-1} mid-flame wind speed), the Froude numbers are in the range of 0–1.1 based on an estimated surface flame height of 1.0 m from reported field observations. Therefore, mean wind speeds of 1.5 and 1.8 m s^{-1}

were selected for detailed experimental investigation, which results in Froude numbers of 0.6 and 1.1. These wind speeds are consistent with those studied by Tachajapong *et al.* (2009), albeit in an open environment.

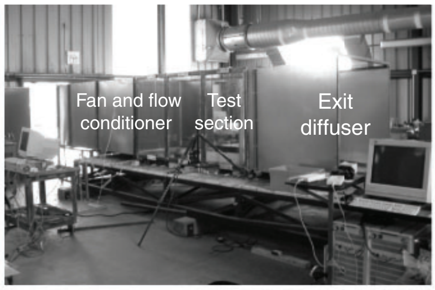
Canopy structure (e.g. shape, depth, pattern and homogeneity) has long been known to influence understorey micrometeorology and surface fire behaviour (Meroney 2007), which in turn influences the onset of crown fire in the presence of wind. In California, chaparral stands range from an almost closed canopy to relatively open canopy with gaps and a large percentage of bare ground (a canopy cover ~30%) which influences the flow field within the canopy (Raupach *et al.* 1986; Keeley 1992; Kanda and Hina 1994). It is now well known that canopy turbulence and exchange is dominated by large eddies with length scales comparable to canopy height, as opposed to a simple augmentation of boundary layer turbulence with turbulence generated by small eddies shed in the wakes of branches and leaves in a canopy (Belcher *et al.* 2008). Thus, simplified, repeatable, laboratory-scale experiments were conducted to investigate the effects of varying wind speed on shrub crown fire initiation under two wind setup configurations; an open-stand wind setup in open air, referred to as open configuration and a closed stand setup in a wind tunnel in which the roof of the wind tunnel is open but lateral entrainment is curtailed because of the presence of side walls. In the open-stand wind setup, wind was generated by three fans each with diameter of 48 cm, placed adjacent to each other without diffuser and the lateral walls to control the flow. The variations of wind velocity in the streamwise direction along the surface fuel bed length and height were thus moderate. However, fresh air can be entrained into the surface fire liberally from the surroundings. This allows lateral entrainment to influence both the surface fire behaviour and the ignition of crown fuel, representing chaparral stands with a large percentage of bare ground. The mean wind speeds at the beginning of the location of the crown fuel were controlled at 1.5 and 1.8 m s^{-1}. In the wind tunnel, experiments can be performed under well-controlled flow conditions, compared with experiments in the open environment. In addition, lateral entrainment was eliminated by the placement of lateral walls in the tunnel. By eliminating a wall on the top side, the fire plume was allowed to rise without any obstruction. Fresh air was allowed to entrain into the surface fire only from the upwind and downwind sides, typifying a closed canopy ecosystem. In both instances, the flow is akin to that encountered in a forest edge where the mean flow adjusts to the canopy drag leading to a wind profile similar to a mixing layer located above the canopy (Belcher *et al.* 2008; Dupont and Brunet 2008). Thus, the differing configurations influence surface fire behaviour although the imposed, upstream wind speed and surface fuel conditions were identical. Tachajapong *et al.* (2009) described the open-stand wind setup in detail in their laboratory studies that focussed on transition from a surface fire to crown fire. Thus, only the wind tunnel setup is described in detail in the current paper as they are consistent in all but the presence of side panels.

Wind tunnel design

For the closed-stand wind tunnel setup, a push type wind tunnel in which a fan is located upstream of the test section was designed for fire experiments to mitigate the unrealistic effects that could occur in the downwind regime of the fire front. A photograph of the arrangement appears in Fig. 1*a* and a detailed schematic in Fig. 1*b*. The lateral walls are made of transparent acrylic sheets. Air flow was generated by a 1.2-m axial fan driven by a 1 HP, three-phase, 240 V, electric motor. A micro inverter, with an output frequency of 0–50.0 Hz and a set point resolution of 0.1 Hz, was used for speed control. This allows the fan speed to be controlled by means of a digital microprocessor. The length of the exit diffuser section of the wind tunnel is 3.00 m. The test section length is 2.40 m. The cross-section is 1.20 m wide and 1.20 m high. The top side of the test section is open, thereby keeping the fire front unconstrained. The mean wind speed, averaged over the entire cross-section, is in the range of 0.8–1.8 m s^{-1} at the location of the crown fuel matrix. More details on the wind tunnel characteristics including measurement locations are presented in results and discussion.

Because the fan blows an undesired distorted turbulence air stream into the tunnel, it is essential to minimise these distortions and turbulence effects by installing a combination of honeycomb and screens next to the fan to create an initially uniform flow. The arrangement of the flow conditioner section in the current wind tunnel consists of one honeycomb with one screen upstream of the honeycomb, followed by two screens downstream of the honeycomb. Following these two screens,

(*a*)



(*b*)

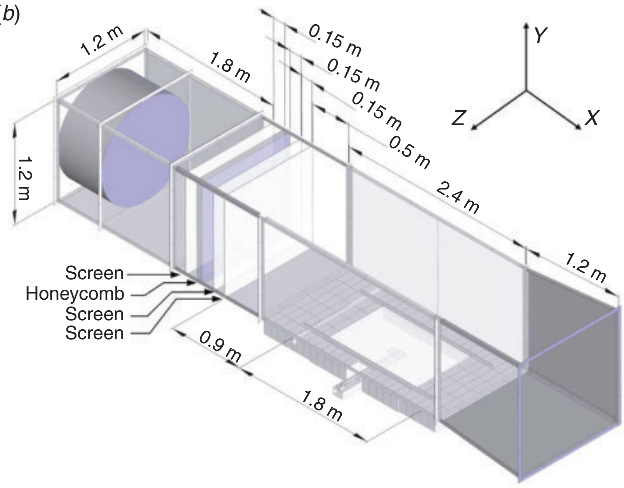


Fig. 1. Illustration of (*a*) a photograph and (*b*) a detailed schematic of the wind tunnel set up. Note that the test section includes lateral walls, with the top open to the ambient laboratory environment. Also shown is the coordinate system utilised in the paper.

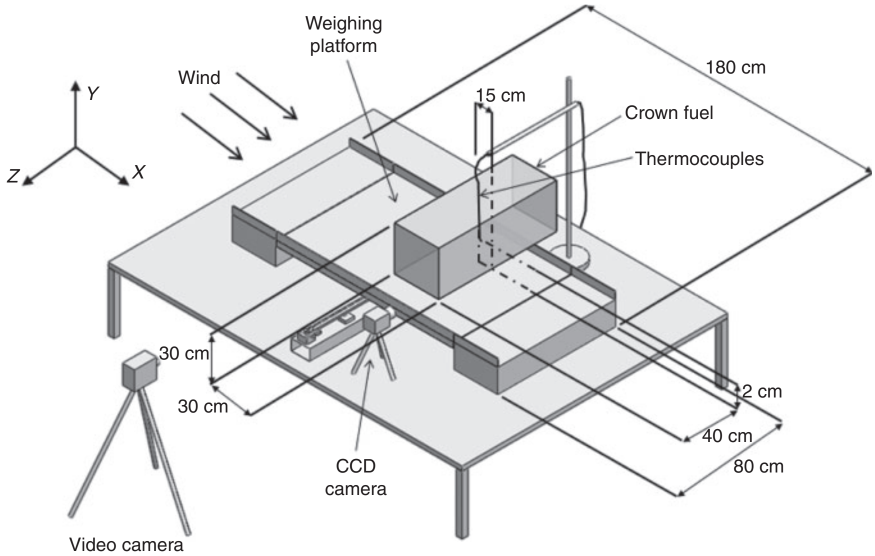


Fig. 2. Schematic of the experimental setup. The location of thermocouples is noted in this figure.

there is a short 50-cm flow straightening section before the airflow enters the test section. The honeycomb is a very effective flow straightening device. With a sufficient length of ~10 cell diameters, it breaks up eddies larger than the cell size and reduces turbulence in the flow, especially the swirl and lateral components of turbulence (Bradshaw and Pankhurst 1964; Loehrke and Nagib 1976; Scheiman and Brooks 1981). For the current wind tunnel setup, the honeycomb cell (Plascore Polycarbonate Core Type PCFR Cell Size: 1/4 colour: white, size: 7.6 cm thick × 1.2 m wide × 1.2 m high) is 6.4 mm in diameter and 76.2 mm long and thus, the length-to-diameter, or aspect ratio of the cells is ~12. The screen will render the flow velocity profiles more uniform by imposing a static pressure drop. The standard wire cloth with the open area of 52.4%, in which the length and height of each screen cell is 1.524 mm and the wire diameter is 0.584-mm screen with a pressure drop coefficient of 2, was chosen because it can eliminate nearly all variations in the longitudinal mean velocity (Mehta and Bradshaw 1979). The spacing between the screen and the honeycomb is 15 cm which is larger than 30 times the mesh size needed to reduce wire generated turbulence (Groth and Johansson 1988). The distance between the last screen and the test bed is 0.50 m and is larger than the minimum requirement of 0.24 m (which is 0.2 times the wind tunnel width) to reduce wire generated turbulence and a distortion of the flow through the last screen (Mehta and Bradshaw 1979).

Deployment of thermocouples

The experiments were set up in a manner identical to Tachajapong *et al.* (2009) as shown in Fig. 2. This figure also indicates the location of thermocouples. A Canon ZR40 video camera was used to capture video images perpendicular to the direction of spread of the surface fire to measure the characteristics of surface fire i.e. rate of spread, flame height, flame depth and flame tilt angle. The rate of spread is obtained by video images. Flame height was defined earlier in this section, consistent with the definition by Merrill and Alexander (1987). Flame depth is defined as the average over time of distance between leading and trailing edges at the fuel surface of a spreading surface fire, and flame tilt angle is the time-averaged angle between the visible flame and the horizontal. Two 30 gauge (0.25-mm diameter) type K (chromel–alumel) thermocouples (Omega Engineering Inc., Stamford, CT, USA) with a response time of 0.29 s were used to record the temperatures of the crown fuel and hot air from the surface fire at a frequency of 2 Hz. An averaging process over 1.5 s was used to filter the temporal fluctuations in each single-point temperature measurement. The space between these thermocouples was less than 2.0 cm. 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. The thermocouples are located inside the crown fuel (~2 cm above the crown fuel bed) as shown in Fig. 2. Because the thermocouple radiates heat to cooler surroundings outside the flame, radiation correction was applied (Cox and Chitty 1985) and the temperature of the hot gas was corrected by ~63 K for a thermocouple reading of 900 K.

Measurement of mass loss rate

In addition to the experimental setup described in Tachajapong *et al.* (2009), a weighing platform was set up to measure the mass loss of the surface fuel. A 1.2 × 0.8-m Kaowool board (Thermal Ceramics Inc., Augusta, GA, USA) covered with a welding blanket was used as a weighing pan. It was placed directly on one end of an 80.0-cm beam with a friction-free ball bearing hinge at the other end. The beam was supported by a load cell (with weight range of 0–11.3 kg), located 25.0 cm from the pivot point as shown in Fig. 3. This results in a mechanical advantage of 3.2. With an actual fuel mass ~325 g, the load cell will read 1040 g and the error would be 21 g (given that the accuracy of load cell is 2%). The load cell was located outside the fuel bed to minimise the heat transfer from fire to load cell. For each experimental run, the tare mass of the weighing pan was

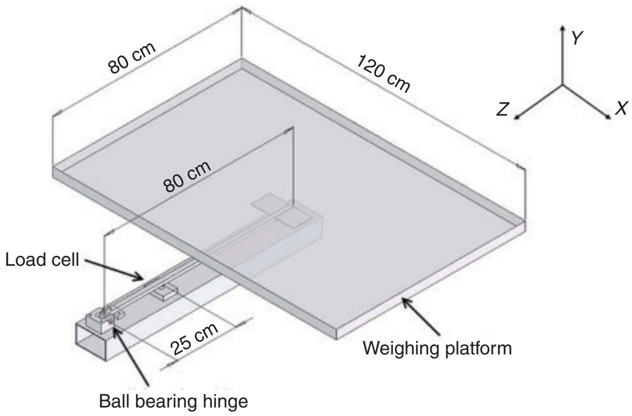


Fig. 3. Illustration of a weighing platform.

measured, the fuel was placed on the pan, the surface fuel mass loss over time was recorded and the residual mass was then determined. The mass loss rate was calculated by differencing two sequential mass measurements over time, and dividing by the time interval (i.e. 0.5 s) between these successive measurements.

Surface and crown fuel arrangement

The experimental conditions including surface and crown fuel characteristics were set up in a manner similar to that reported by Tachajapong *et al.* (2009). Surface fuel comprised 0.45 kg of aspen (*Populus tremuloides*) excelsior, evenly distributed over a 0.8 m-wide, 1.8 m-long, flat surface to a depth of 0.1 m. This fuel bed resulted in a surface fire with the flame height in the range of 0.3–0.5 m under the ambient conditions in the laboratory (ambient temperature without wind, $T = 298$–305 K, ambient relative humidity, RH = 20–37%). Surface fuel bulk density, fuel particle density, surface-to-volume ratio, heat of char combustion, char content and ash content of the excelsior were 3.13 kg m^{-3}, 400 kg m^{-3}, 4000 m^{-1}, 32.37 MJ kg^{-1}, 15.40% and 0.35% (Susott 1982). In this study, the surface fuel bulk density refers to the oven dry mass of small fuel particles (less than 3 mm in diameter) per unit volume of surface fuel. Fuel moisture of the excelsior was not controlled. The dry-basis moisture content of excelsior was estimated to be in the range of 4.3–7.2%. Rapid ignition of a line fire was accomplished by using a propane gas 'log lighter' in the wind tunnel. The 'log lighter' was a steel pipe with a line of 3.2-mm holes spaced 40 mm apart. Approximately 2 mL of ethyl alcohol was sprayed uniformly over an area 0.8×0.05 m at one end of the fuel bed. Ignition was accomplished at the centre of the line with a hand-held butane lighter and a line fire was established in less than a second. In both cases, ignition was typically established in less than 3 s.

The crown fuel bed was composed of freshly cut chamise (*Adenostoma fasciculatum*) branches and foliage (foliage diameter $\approx$ 0.5 mm, branch diameter $\approx$ 3.5 mm). It was experimentally determined that the typical mass-based proportions of foliage and branch were ~53 and 47%. The physical properties of foliage were 500 kg m^{-3}, 8000 m^{-1}, 31.35 MJ kg^{-1}, 28.60% and 3.50% for the fuel particle density, surface-to-volume ratio, heat of char combustion, char content and ash content (Susott 1982). The corresponding properties for the branches were 600 kg m^{-3}, 1143 m^{-1}, 31.35 MJ kg^{-1}, 14.30% and 0.50%, (Ragland *et al.* 1991). The crown fuel comprised similar-sized chamise branches with foliage arranged in a volume with dimensions $0.30 \times 0.30 \times 0.80$ m in height, length and width. The crown fuel was placed on a coarse, 0.9-mm steel wire mesh with 85% open area. The oven-dry weight basis moisture content of fuel sample was measured a few minutes before each experiment using an Computrac MAX 1000 moisture analyser (Arizona Instrument LLC, Chandler, AZ, USA). In this study, the crown fuel bulk density refers to the combined mass of oven dry foliage and small twig (foliage diameter $\leq$0.5 mm, branch diameter $\leq$3.5 mm) per unit volume of canopy (Van Wagner 1977; Alexander 1988; Finney 2004; Keane *et al.* 2005). Noting that foliage and small twig of chaparral in the field are mostly present in the middle portion of canopy (D. R. Weise, unpubl. data), it is estimated that the crown fuel bulk density is ~1.41 times higher than that of the average value. Accordingly, the crown fuel bulk density in this portion could be in the range 0.28 kg m^{-3} to 2.96 kg m^{-3}. However, a high crown fuel bulk density (6.79 kg m^{-3}) with low crown fuel base height (0.20 m) was selected in our experiments, as it is close to an upper limit at which hot smoke from the surface fire is impeded by the crown fuel (Tachajapong *et al.* 2008), ensuring the high possibility of successful crown fire initiation. The dry-basis moisture content of chamise (both the foliage and the branch) was in the range of 40–88%. The ambient temperature was in the range of 298–305 K with relative humidity in the range of 20–37%. A randomised design was used to ensure that the experimental effects 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.

Results and discussion

Wind tunnel characterisation

A constant temperature hot-wire anemometer (Omega Engineering Inc., model FMA-604-V) was used to measure the mean streamwise wind velocity profile, both as a function of vertical height and streamwise distance. The velocity profiles were measured along the surface fuel length in a vertical plane perpendicular to the wind direction at 0.0, 0.5, 1.0, 1.5 and 1.8 m from the leading edge of surface fuel bed. The value at each distance was the averaged value from 9 points distributed equally across vertical plane as shown in Fig. 4*a*. The mean velocity variation with height above the surface fuel bed was measured at the location of the crown fuel matrix which is 1.2 m from the beginning of surface fuel bed. The value at each height (i.e. at 0.0, 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 m above surface fuel) is the averaged value from three points distributed equally across the width of a vertical plane perpendicular to the wind direction as shown in Fig. 4*b*. As a demonstration of the uniformity of the resulting wind profile and very low turbulence intensity, a relatively low wind speed of 0.8 m s^{-1} and a maximum wind speed of 1.8 m s^{-1} that can be established in the wind tunnel are chosen to show variations in mean streamwise wind velocity, and turbulence intensity profiles in Figs 5 and 6. From Figs 5 and 6, it can be seen that the wind velocities along the surface fuel bed length are relatively constant as shown in Figs 5*a* and 6*a*. They decay slightly (less than 3%) due to the open roof of the testing section. The velocity is relatively uniform with vertical height as shown in Fig. 6*a, b*. The maximum variation with height was ~4% at a height of 0.6 m above the ground (as compared with 15% in the case of the open-stand wind setup). Thus, the profiles were relatively uniform throughout the entire cross-section and for the entire range of wind speeds studied, which is very good compared with the open-stand wind setup (see Tachajapong *et al.* 2009).

It was also found that the turbulence intensity is below 0.02 for all of the measurement area as seen in Figs 5 and 6. Turbulence intensity is defined as $I = U_{ms}/U_{wind}$ where U_{rms} is root mean square of streamwise velocity fluctuation and U_{wind} is the streamwise mean velocity. It is fairly evenly spread out over the measurement area with a slight increase towards the central region. The averaged turbulence intensity over the measurement area is 0.01. It is noted that the turbulent intensities are ~2.5 times the mean wind speed under field conditions. This value is estimated based on Santa Ana wind in which the average wind speed is in the range of 10–30 m s^{-1} with wind gusts exceeding 50 m s^{-1}. The desired turbulent intensity is generally less than 0.1 for wind tunnel design.

Effects of increasing wind speed

Two wind velocities of 1.5 and 1.8 m s^{-1} were chosen for detailed investigation of fire behaviour. For the present paper in which experiments were performed in the wind tunnel, it was noticed that the tunnel walls affect the fire-surface fuel interaction because the surface fire depth, height and spread rate increased in contrast to experiments conducted in an open environment at the same wind speed (Table 1). The situation, in which the side walls of the wind tunnel were removed, is referred to here and elsewhere in this paper as open environment experiments. They correspond to the cases previously reported by Tachajapong *et al.* (2009). In all cases considered, flame height was measured from the bottom of the surface fuel. The cooling effect from fresh air entrainment via the lateral edges of surface fire is blocked by the wind tunnel walls which lead to an increase in the temperature of hot gaseous products. Thus, radiative energy transfer to the unburned surface fuel could be enhanced. Consequently, the rate of pyrolysis gases released from the surface fuel could increase so that the flame size enlarged and the rate of spread increased.

At a wind speed of 1.5 m s^{-1}, the average visible flame height over time increased to 0.38 m (with a standard deviation of

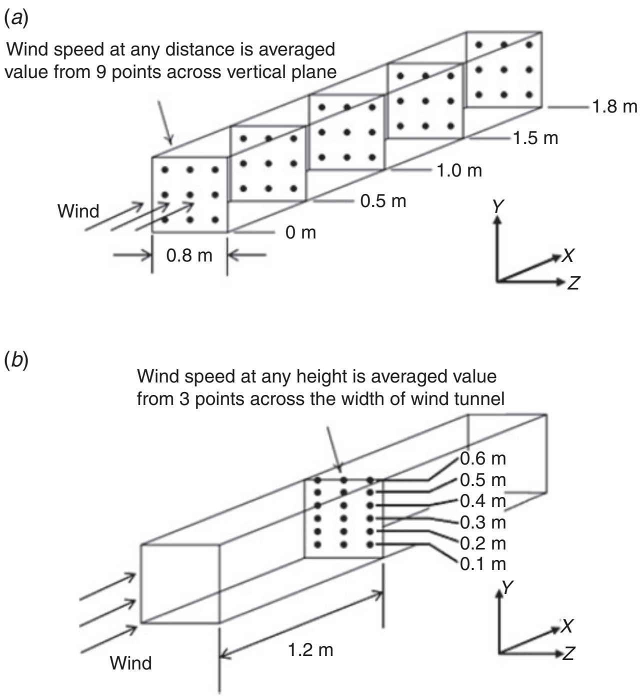


Fig. 4. Wind velocity measurement (*a*) along the surface fuel bed length and (*b*) with height above surface fuel bed at 1.2 m from the beginning of surface fuel bed (the location of the crown fuel matrix).

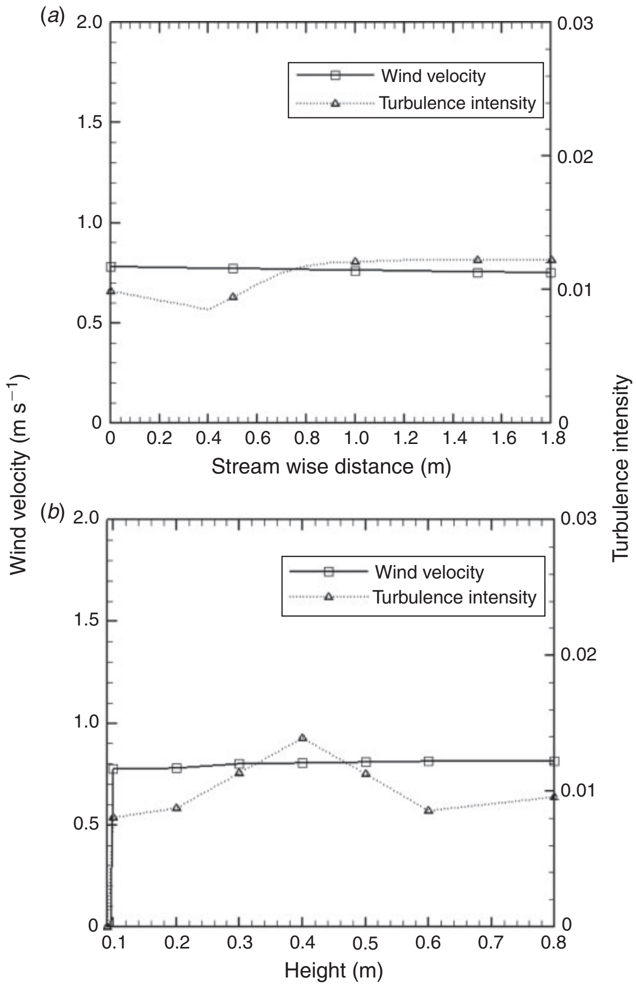


Fig. 5. Mean stream wise wind velocity and turbulence intensity profiles at low wind speed setting (*a*) along the surface fuel bed length representing an average value across a vertical plane of 1.2 m wide by 1.2 m high and (*b*) with height above surface fuel bed at 1.2 m from the beginning of the surface fuel bed.

0.08 m) as compared with 0.34 m (with a standard deviation of 0.03 m) in the case of the open environment experiments (Tachajapong *et al.* 2009). In the open environment experiments, note that the side walls of the wind tunnel were removed, thereby permitting lateral entrainment. The surface fire was responsive to buoyancy forces originated from surface fire because the hot gas still moved upward while the flame tilted forward as can be seen in Fig. 7*a*. Also noted in this figure are three regions, the continuous flame region in which flame surface exists at all times, intermittent flame region characterised by flames appearing intermittently in this range of height above the surface fuel, and the hot plume region in which no flame exists. The minimum and maximum flame heights were 0.25 and 0.65 m. The minimum flame height was higher when compared with results in the open environment (Tachajapong *et al.* 2009). The crown base of 0.20 m was thus situated within the continuous flame region of the surface fire as shown in Fig. 7*b* in contrast to the intermittent flame region in the open environment. The flame depth evidently increased from 0.38 m (open) to 0.61 (tunnel) when the tunnel wall blocked the fresh cool air flowing from the outside of the walls. This should be further investigated in the future because the reduction in fresh air entrainment into the surface fire may be the important factor affecting surface fire behaviour. Thus, the tunnel walls were certainly affecting the ignition of crown fuel because the flame depth of the surface fire is an important factor affecting the ignition of crown fuel (Cruz *et al.* 2006). The average rate of spread increased to 5.5 cm s^{-1} with a standard deviation of 0.2 cm s^{-1} (as compared with an average rate of spread of ~3.2 cm s^{-1} with standard deviation of 0.1 cm s^{-1} in the open environment).

When the wind speed increased from 1.5 to 1.8 m s^{-1}, the surface fire tilt angle increased as the fire behaviour was dominated by the inertial force from wind as shown in Fig. 7*c*. The hot smoke trajectory was tilted towards the unburned fuel. The minimum and maximum flame heights were 0.20 and 0.60 m. The crown base of 0.20 m was situated within the continuous flame region of the surface fire as shown in Fig. 7*d*. In comparison with experiments conducted in an open environment at the same wind speed, the average rate of spread of surface fire increased significantly from 3.9 to 12.0 cm s^{-1} (with a standard deviation of 1.3 cm s^{-1}) and the average visible flame height increased from 0.32 to 0.36 m with a standard deviation of 0.09 m, and the minimum flame height increased from 0.15 to 0.20 m. The flame depth increase from 0.62 to 1.02 m resulted in a successful ignition of the crown fuel (as compared with unsuccessful ignition in the open environment).

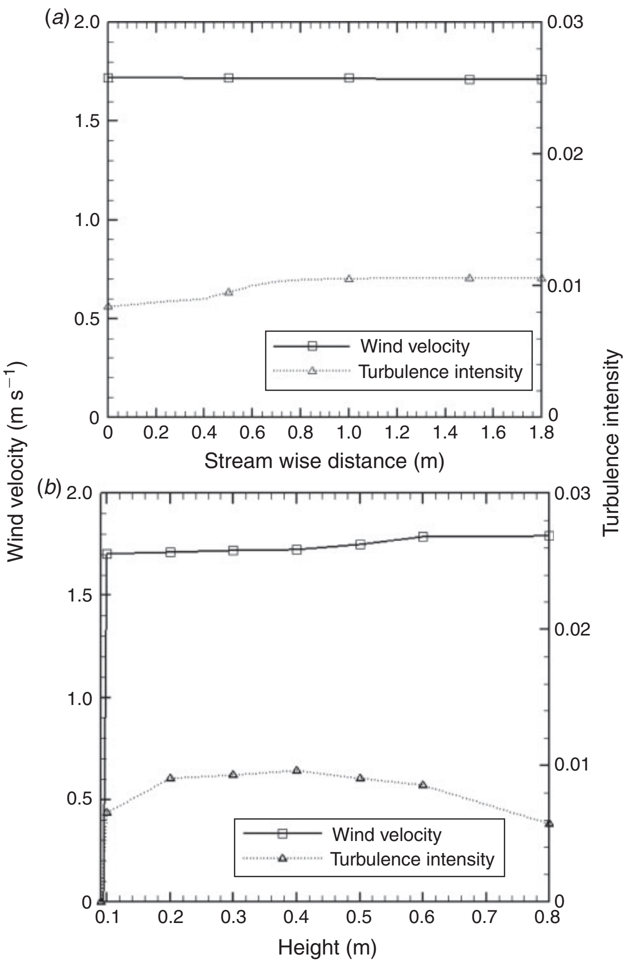


Fig. 6. Mean stream wise wind velocity and turbulence intensity profiles at high wind speed setting (*a*) along the surface fuel bed length representing an average value across a vertical plane of 1.2 m wide by 1.2 m high and (*b*) with height above surface fuel bed at 1.2 m from the beginning of the surface fuel bed.

Table 1. Experimental results on crown fire transitions at different wind conditions

Crown base height is 0.20 m and all experiments were repeated three times for each condition. Flame depth is defined as the distance between leading and trailing edges at the fuel surface of a spreading surface fire. Flame depth and flame tilt angle are obtained from video images and thus have the standard error from reading of 0.05 m and 15°. $MC_{surface}$, moisture content of surface fuel; MC_{crown}, moisture content of crown fuel; $T_{a,c}$, hot gas temperature at the bottom of crown fuel. All values are ±standard deviation

Wind (m s^{-1})	$MC_{surface}$/MC_{crown} (%)	T_a (K)	*RH* (%)	Flame height (m) Minimum	Average	Maximum	Flame depth (m)	Flame tilt angle (°)	*ROS* (cm s^{-1})	$T_{a,c}$ (K)	Ignition success
0	7.0 ± 0.4/84 ± 2	300 ± 2	36 ± 2	0.15	0.30	0.45	0.10	0	1.9 ± 0.1	586 ± 62	Yes[A]
1.5 ± 0.2 (open)	6.8 ± 0.1/88 ± 3	305 ± 1	35 ± 1	0.20	0.34	0.65	0.38	38 ± 2	3.2 ± 0.3	659 ± 76	Yes[A]
1.5 ± 0.2 (tunnel)	4.4 ± 0.1/40 ± 2	303 ± 1	21 ± 1	0.25	0.38	0.65	0.61	42 ± 1	5.5 ± 0.1	858 ± 72	Yes
1.8 ± 0.2 (open)	7.2 ± 0.0/84 ± 2	298 ± 1	37 ± 0	0.15	0.32	0.60	0.62	50 ± 1	3.9 ± 0.2	623 ± 69	No[A]
1.8 ± 0.2 (tunnel)	4.4 ± 0.2/41 ± 1	303 ± 1	20 ± 1	0.20	0.36	0.60	1.02	54 ± 1	12.0 ± 1.3	704 ± 109	Yes

[A]The results are from Tachajapong *et al.* (2009) for mean velocities of 0, 1.5 (open), and 1.8 m s^{-1} (open).

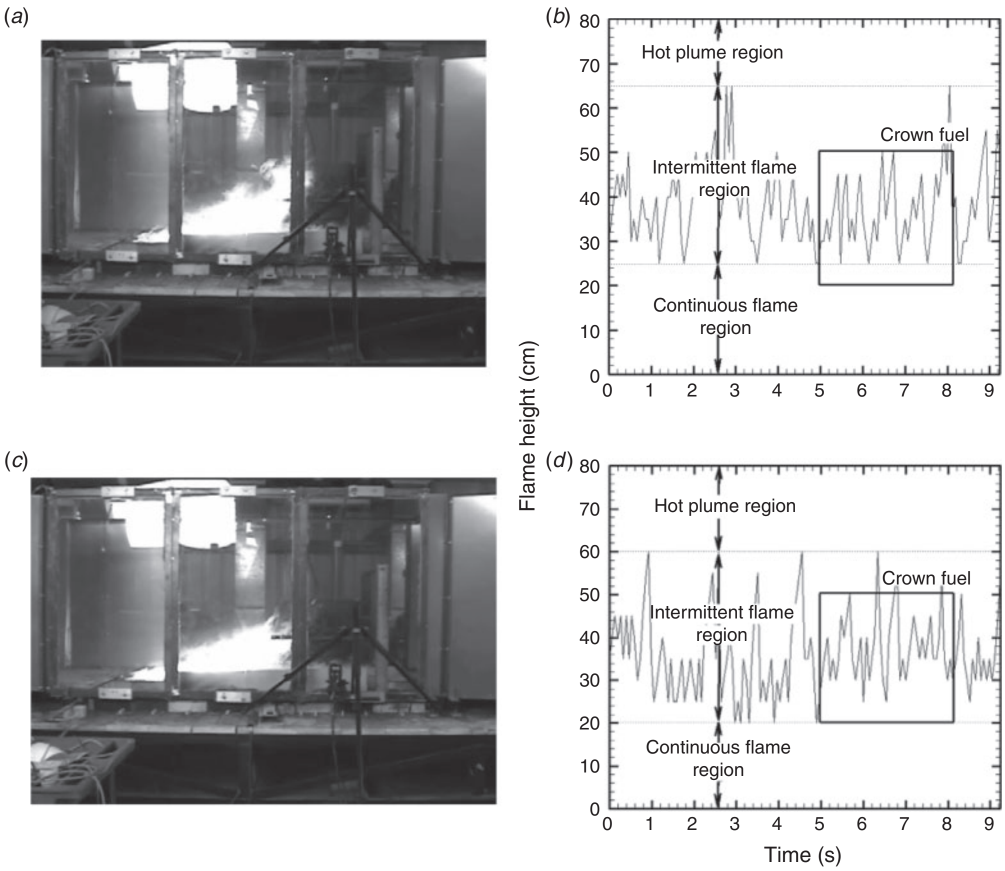


Fig. 7. Illustration of spreading of surface fire and flame height in the wind tunnel under wind speed of 1.5 m s^{-1} (*a, b*) and under wind speed of 1.8 m s^{-1} (*c, d*) (crown base height is 0.20 m, wind and fire spread direction is from left to right in both cases).

Thus, the wind tunnel imposed different surface fire properties in comparison to experiments in an open environment. It is noted that the times and locations at which the crown fuel ignited could not be observed in the experiments because the crown fuel ignited while surface fire was spreading below it. The entire crown fuel was burning when the surface fire passed the crown fuel. The surface fuel moisture content for the experiments conducted in the wind tunnel (i.e. 4.3–4.7% dry basis) is also not significantly lower than those performed in the open environment (i.e. 6.7–7.2% dry basis) due to different ambient conditions, and reflects our inability to exercise control of this parameter. Thus, it is clear that the suppression of lateral entrainment is important in influencing surface fire behaviour under the effects of a steady wind and is also an important factor affecting the ignition of crown fuel if surface fuel is highly flammable.

At a wind speed of 1.8 m s^{-1}, it was found that the tunnel walls affect surface fire characteristics. Bryant (2009) described a fire-induced flow in an enclosure in which the hot plume acts as a source to push hot gas to escape from the upper portion of the enclosure while simultaneously acting as a sink to induce fresh air from the ambient into the lower portion of the enclosure. Lozano (2008) postulated that the formation of large scale vortices may occur as a result of the shear flow between the hot plume and the fresh air that is entrained into the surface fire. These large scale vortices were observed and their basic properties measured in Lozano's experiment. They affected the rate of spread of surface fire as more convective energy can be transferred to surface fuel ahead of the surface fire front in addition to the radiative energy transfer. Although the present experimental diagnostic tools were not designed to observe large scale vortical structures, given the similarity to Lozano's experimental set up, they exist in all likelihood. Therefore, it is possible that the tunnel walls may not only affect cooling effect but they may also influence the fluid dynamics and heat transfer mechanism especially at higher wind speeds.

Mass loss rate measurement and thermocouple measurement results

The time evolution of mass loss rate of surface fuel (*ML*) and gas phase temperature (T_a) inside the surface fuel layer located 0.20 m from the leading edge of the weighing platform for wind speeds of 1.5 and 1.8 m s^{-1} (with and without crown fuel) is shown in Fig. 8 and time evolution of surface fuel mass on the weighing platform is shown in Fig. 9. At a mean wind speed of 1.5 m s^{-1}, the peak mass loss rate was 10.6 g s^{-1} (shown to be repeatable to ±3.2 g s^{-1}) with the gas phase temperature inside

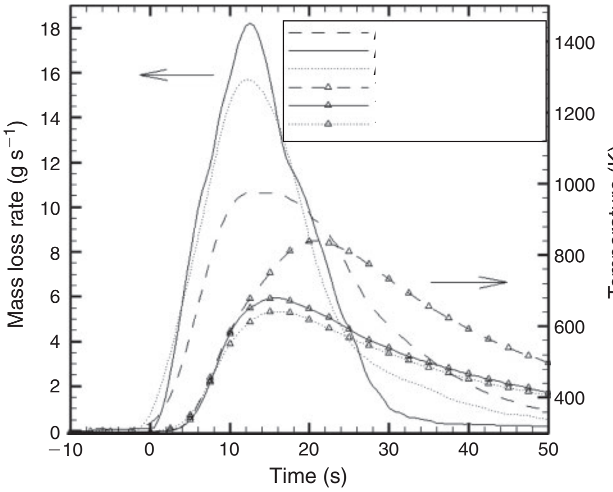


Fig. 8. Time evolution of mass loss rate of surface fuel and gas phase (T_a) temperature inside the surface fuel layer located at 0.20 m from the leading edge of the weighing platform (crown base height is 0.20 m with wind speed of 1.5, 1.8 m s^{-1}, or 1.8 m s^{-1} without crown fuel).

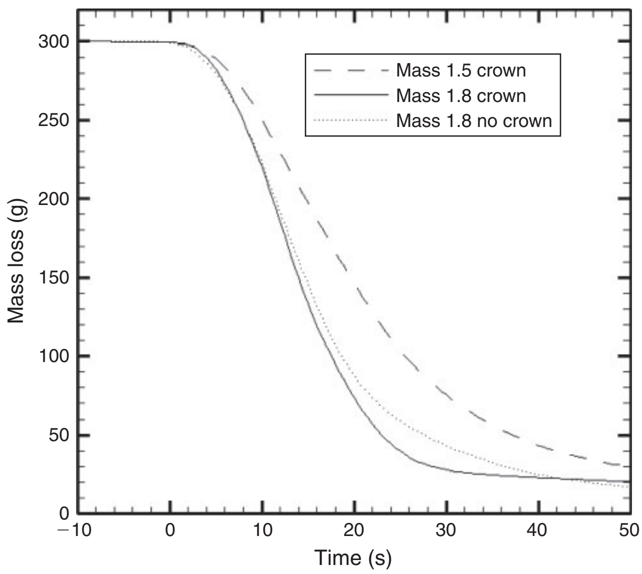


Fig. 9. Time evolution of surface fuel mass on the weighing platform (crown base height is 0.20 m with wind speed of 1.5, 1.8 m s^{-1}, or 1.8 m s^{-1} without crown fuel).

the surface fuel layer of 839 K (shown to be repeatable to ±51 K). When the wind speed increased to 1.8 m s^{-1}, the peak mass loss rate increased to 18.2 g s^{-1} (shown to be repeatable to ±3.0 g s^{-1}) and the rate of combustion of the surface fire (and hence the fire spread rate and intensity) increased as the wind speed increases. However, the higher wind speed increased the velocities of the hot plume gases so more fresh air was inducted into the lower portion of the flame front. Because combustion occurs above the surface fuel layer, the gas phase temperature inside the surface fuel layer decreased to 679 K (shown to be repeatable to ±49 K). It was also noticed that the cool air entrainment from the downstream side of the fire front may affect the surface fire behaviour at the wind speed of 1.8 m s^{-1}. The crown fuel may block air ventilation from downstream side and affect surface behaviour. Without the presence of crown fuel, air can flow freely in the downstream zone of the surface fire. This may increase hot gas exhaust from the surface fire or fresh air entrainment into the surface fire, thereby reducing the hot gas temperature. A specific experimental setup to determine the effect of air flow from downstream may be useful. In this case, the combustion rate decreased as is observed from the reduction in the peak mass loss rate from 18.2 g s^{-1} (shown to be repeatable to ±3.0 g s^{-1}) to 15.7 g s^{-1} (shown to be repeatable to ±3.5 g s^{-1}). As a result, the gas phase temperature inside the surface fuel layer decreased from 679 to 641 K (shown to be repeatable to ±34 K). However, the differences in the results between the presence and absence of crown fuel at the wind speed of 1.8 m s^{-1} were not significant in the current study as the crown fuel size was set up to focus on the crown fire initiation process. The crown fuel dimension may be a significant factor that affects the flow characteristics in the downstream region of the surface fire which consequently affects the convective cooling from the downwind regime of the fire front. Thus, further investigation with more specific experimental setup may reveal more effects of the presence of the crown fuel on surface fire behaviour.

A comparison of time evolution of air (T_a) and solid phase (T_s) temperature of the branch inside crown fuel between the open environment case and similar experiments in the wind tunnel including side walls, for wind speeds of 1.5 and 1.8 m s^{-1} is shown in Fig. 10. At a wind speed of 1.5 m s^{-1}, from Fig. 10*a*, it is evident that both the temperature of the hot gas at the bottom of crown fuel and the residence time of convective heating increased in comparison to experiments in an open environment. Note that the measured temperature of the crown fuel increased from 659 ± 76 to 994 ± 18 K. Likewise, the residence time, defined here as the time interval over which the hot gas temperature measured within the crown fuel stays above 500 K increased from ~9 to 16 s (Because the crown fuel ignited in all experiments conducted in the wind tunnel; the residence time of 16 s, as can be seen in Fig. 11, was obtained by measuring hot gas temperatures at crown base level from the experiments of fire spreading without crown fuel.). It is noted that the hot gas plume trajectory shape cannot be seen by the naked eye and is different from the visible flame shape. Therefore, the residence time of convective heating is not directly proportional to the fire depth. Thus, the net energy transfer to crown fuel was high enough for raising temperature of crown fuel to ignition temperature in the wind tunnel with side walls in place and was much higher than that in the open environment so the crown fuel was ignited successfully as shown in Fig. 12*a*. At a higher wind speed of 1.8 m s^{-1}, see Fig. 10*b*, wind increased the surface fire height and depth so that the hot gas temperature in the region below the crown fuel matrix increased to 1141 ± 53 K (compared with 623 ± 69 K in the open environment) and ~24.0 s (compared with 7.5 s). (The residence time of 24 s, as can be seen in Fig. 11, was obtained by measuring hot gas temperatures at crown base level from the experiments of fire spreading without crown fuel.) The net heat transfer to the crown fuel was thus sufficient to ignite the crown fuel. The crown fire was successfully initiated after the surface fire passed the crown fuel as is evident from Fig. 12*b*.

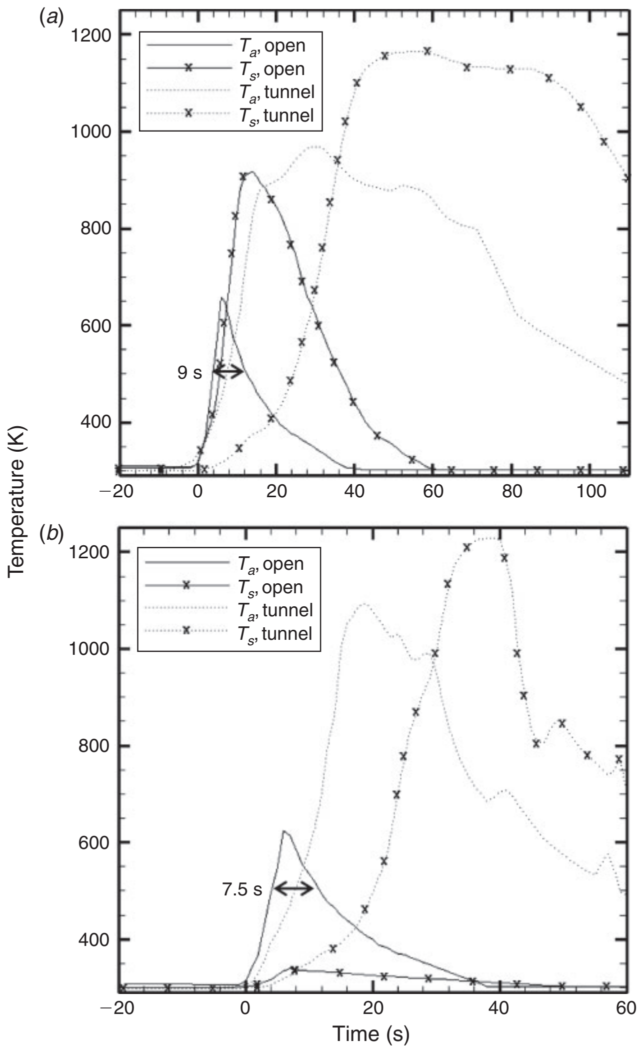


Fig. 10. Time evolution of experimental air (T_a) and solid phase (T_s) temperature of the branch inside crown fuel under wind speed of (*a*) 1.5 m s^{-1} and (*b*) 1.8 m s^{-1} (crown base height is 0.20 m).

Therefore, it is clear that increasing wind speed increases the propensity for crown fire initiation in the wind tunnel. This observation is in contrast to results obtained in the open environment wind setup, in which increasing wind speed decreases the tendency of crown fuel initiation. Thus, the lateral entrainment is an important factor when examining the onset of crown fire under the presence of wind. It directly influences the fluid dynamics associated with the heat transfer processes between surface fire and the unburned fuel located ahead of the flame front. In this study, it has an effect on the convective cooling to the surrounding which directly controls the surface fire characteristics. The change in surface fire behaviour significantly affects the convective energy transfer to the unburned surface and crown fuels. All experimental results on crown fire transitions at different wind speed of 0, 1.5 and 1.8 m s^{-1} at a fixed crown base height of 0.20 m in both the open environment and wind tunnel setup are summarised in Table 1.

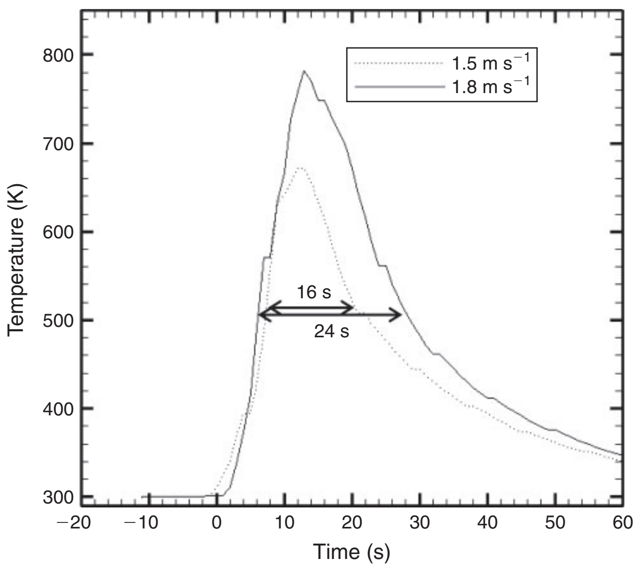


Fig. 11. Time evolution of experimental air temperature (T_a) measured at crown base level (0.2 m above the ground fuel) under wind speed of 1.5 and 1.8 m s^{-1} without crown fuel.

For the current experimental conditions, it could be concluded that increasing wind speed will increase the propensity for crown fire initiation in the closed surrounding (e.g. a closed canopy ecosystem). This agrees with studies of Alexander (1988), Xanthopoulos (1990), and Scott and Reinhardt (2001) in which wind increases the likelihood of crowning due to increasing surface fire spread rate and intensity. However, increasing wind speed will decrease the tendency of crown fire initiation in the open environment (e.g. open stand tree with a large percentage of bare ground). This shows the same trend as studies of Luke and McArthur (1978) that increasing wind speed increases the flame tilt angle so that the convective hot plume has less contact with the crown fuel. The energy transfer from surface to crown fuel also decreases by heat loss to the surrounding as reported by Plucinski (2003). Thus, based on the experimental results presented and analysed, one can note that in southern California, wildfires in chaparral stands with almost a closed canopy ecosystem may have a higher tendency to develop into high-intensity fires under the influence of wind as compared with wildfires in chaparral stands with many large gaps and high percentage of bare ground. The accuracy of operational models, applied to predict shrub canopy crown fire initiation, may be improved when canopy structure is considered to be a factor affecting fire behaviour.

Summary and conclusions

The effect of varying wind speed on the transition of surface fire to live shrub crown fuels was studied through a simplified laboratory-scale experiment. The experiments modelled shrub canopy crown fuel as might be the case in chaparral stands in southern California as well as other shrub types around the world. The dry-basis moisture content of chamise (both the foliage and the branch) was in the range of 40–88%. The ambient temperature was in the range of 298–305 K with

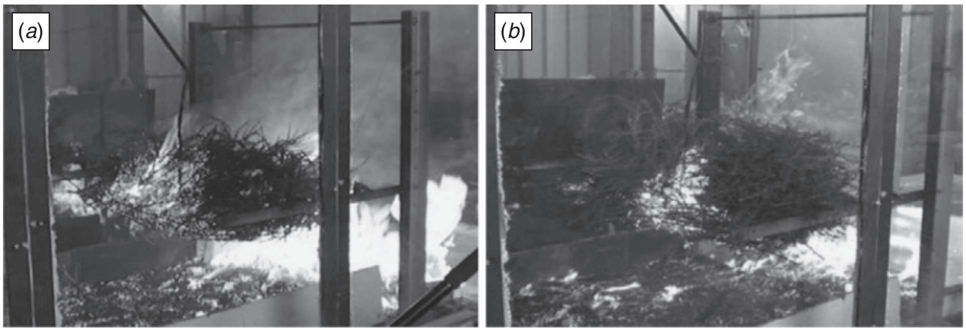


Fig. 12. Ignition of crown fire under wind speed of (*a*) 1.5 $m\,s^{-1}$ and (*b*) 1.8 $m\,s^{-1}$ in wind tunnel (crown base height is 0.20 m, wind and fire spread direction is from left to right in both cases).

relative humidity in the range of 20–37%. Crown base height was 0.20 m. All the experiments in this paper were conducted in a wind tunnel. Mean wind speeds of 1.5 and 1.8 $m\,s^{-1}$ were selected for a detailed investigation which results in Froude numbers of 0.6 and 1.1. Comparisons are made with an open-stand wind set up configuration reported in an earlier paper, Tachajapong *et al.* (2009).

It was found that increasing wind speed decreases the propensity for crown fire initiation in the open environment (as reported by Tachajapong *et al.* 2009), in contrast, in the present closed-stand configuration set up in a wind tunnel, it increases the propensity for crown fire initiation. The results indicate that wind shows strong effects on surface fire behaviour. The change in the characteristics of surface fire significantly affects the convective energy transfer to the unburned crown fuel and the ignition success. In an open environment wind setup that was previously studied, increasing wind speed from 1.5 to 1.8 $m\,s^{-1}$ decreased the possibility of crown fire initiation because of reduced heating. The residence time of convective heating decreased from 9.0 to 7.5 s and the hot gas temperature at crown base decreased from 659 to 623 K so the net energy transfer to the crown fuel decreased. However, increasing wind speed from 1.5 to 1.8 $m\,s^{-1}$ in the current wind tunnel experiments increased the possibility of crown fire initiation. Although the spread rate of surface fire increased from 5.5 to 12.0 $cm\,s^{-1}$ in the wind tunnel, the surface fire depth also increases from 0.45 to 1.02 m so the residence time of convective heating significantly increases from 16.0 to 24.0 s. The hot gas temperature at the crown base also increased from 994 to 1141 K and thus the net energy transfer to the crown fuel increased. This implies that the canopy structure is one of the important factors affecting the onset of crown fire in shrublands. It is noted that the findings are based on a limited set of experimental conditions. However, the results from this study represent a first step in better understanding the phenomenon of transition of a surface fire to a crown fire in shrublands under the influence of wind.

Acknowledgements

The funding source for this research is the USDA/USDI National Fire Plan administered through a Research Joint Venture Agreement number 06-JV-11272166-058 with the Forest Fire Laboratory, Pacific Southwest Research Station, Riverside, CA. W. Tachajapong acknowledges support from the Royal Thai government for an educational scholarship. The authors also express their appreciation to Dr Xiangyang Zhou from FM Global for his assistance in designing the experimental facility.

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