Ember Attack: Its Role in the Destruction of Houses during ACT Bushfire in 2003

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Abstract

The ACT bushfire in 2003 led to enormous loss of natural resources and property, including more than 500 houses at the urban interface. In order to understand how the bushfire affected the adjacent urban area and the reason for the massive destruction of houses in the Duffy area, the fire behaviour in the bushland, especially the formation of embers and their transport, are studied in the current paper. Parameters such as fire intensity, maximum "loftable" size of firebrands, and minimum as well as maximum travel distances downwind, have been evaluated using existing knowledge and established mathematical models. It is found that under the circumstances considered, the area to receive the most effective ember attack should be between 50 and 400 m downwind of the fire source, which is in excellent agreement with the Γ-type distribution of the affected houses at the urban interface. Scatter in the locations of these houses is also a reflection of the random feature of the transport of firebrands and the subsequent spot fires. There is no doubt that ember attack, resulting from the formation of a high-intensity crown fire in the adjacent bushland and the presence of high wind speeds, was a major, though not necessarily prime, contributor to the massive loss of houses in Duffy urban area.

Introduction

The ACT bushfire in 2003 was severe in Australian bushfire experience, partially due to its impact on the urban areas. Most remarkably, late in the afternoon of January 18, 2003, the bushfire swept several through urban areas including Duffy, resulting in the loss of more than 500 houses. As revealed by video taped during the fire and direct observations of witnesses during the fire development in the Duffy area (Moran 2003), the fire was notable for the generation and transport of large amount of embers. Once the bushfire entered the bushland adjacent to the Duffy residential area, embers sourced from the fire field and carried by strong local wind crossed a low fuel zone and a main road, and landed on the houses and surrounding vegetations. This process led to the ignition of houses and their surroundings in many separate locations.

The Duffy residential fire is a typical example of how the bushfire may affect an adjacent built environment. For the purpose of furthering the understanding on the role of embers in affecting the residential area at the interface, the formation of embers and their flow-dynamic features observed in the Duffy area are analysed using the information collected during the fire and previously established knowledge. The relationship between the features of generated firebrands and the fate of the affected residential area is then discussed in these terms.

Fire Environment and Behaviours

Vegetation located in the northern and western outskirts of the flat Duffy residential area are mainly composed of the *Pinus radiata* pine trees planted about 20 years ago, with the heights varying between 12 and 15 m in principle (e.g. Moran 2003). The wind speed recorded by the nearby weather station, was about 40 km h^{-1} between 15:00 and 18:00 on January 18, 2003, from northwest, at an angle of ~50° west from north (Blanchi and Leonard 2005). Before the bushfire approached the Duffy urban area, air temperature was above 35°C and the relative humidity was below 10% (Blanchi and Leonard 2005). These factors constituted an extremely high score on the forest fire danger index (FFDI) (McRae 2003, Chen and McAneney 2004).

Driven by local wind, the fire moved towards the urban interface by igniting a strip of pine trees situated in the north and west boundaries of the Duffy residential area after 15:00. This fire was characterised by burning trunks and canopies of individual pine trees or groups of them (Moran 2003, Blanchi and Leonard 2005), as is typical of crown fires. It burnt fiercely, although the fire frontline normal to the wind direction was not extensive, as shown by the video taped during the bushfire attack on the urban interface (Moran 2003). Flame plumes engulfed the individual trees with the flame tip often higher than the top of the trees. The height of a flame tip varied between 15 and 30 m. It was also observed that, due to the presence of strong local wind from time to time, the flame plumes developed around the tree crowns inclined significantly, with the maximum tilt angle of ~40° from the vertical plane (Moran 2003). Similar results can be obtained for flame tilt angles under the observed conditions of wind speeds and flame lengths using the model of Thomas (Muraszew 1974). Given the impact of such high-intensity crown fire on local weather conditions, it is reasonable to expect that the local wind speed may be sometimes higher than the wind speed elsewhere, with the maximum reaching 55 km h^{-1} or so (Pyne *et al* 1996, Chen and McAneney 2004).

The flame height data can be applied to estimate the fuel consumption rate using the well-known equation $h_f = 10.4\dot{m}_f^{2/5}$, introduced by Albini (1979). The heat release rate of the crown fire is then determined by a multiplication of the fuel consumption rate with the heat of combustion adopted for usual wildland fuels, that is H_c=18,620 kJ kg^{-1} (Pyne *et al* 1996). The fireline intensity I_b is also evaluated using a correlation, i.e. $l_f = 18.6(I_b/H_c)^{2/3}$ (Thomas 1971). The estimated data of fire behaviour are summarised in Table 1.

Table 1 Results of fire behaviour evaluation.

Item	**Evaluated result**	**Comments**
Fuel type	20 year-old pine trees	Searched result over the internet
Flame height (m)	15–30	Retrieved from the video information (Moran 2003)
Flame length (m)	20–35	Results adjusted by considering the inclination effect of flame plumes
Maximum flame tilt angle (°)	~40	Direct measurement from the recorded flame images; confirmed using the Thomas's model (Muraszew 1974)
Fuel consumption rate (kg s^{-1})	2.5–14	Determined based on a model of Albini (1979)
Heat release rate (kW)	47,000–263,000	Calculated from the fuel consumption rate
Fireline intensity (kW m^{-1})	21,000–48,000	Determined by the model of Thomas (1971) and the flame length varying from 20 to 35 m

The maximum heat release rate determined by the current method is roughly a quarter of that reported by McRae (2003), for the burning of forest fuels in three hours on that day. However, the maximum fireline intensity is essentially in agreement with that reported by Gould, who suggested a number of 50,000 kW m^{-1} for the burning of pine trees in the Duffy area (Chen and McAneney 2004).

Due to the high-intensity of combustion over the tree trunks and canopies, strong buoyancy flow may be formed above the burning fuels. As the result of the gaseous buoyancy flow and the presence of local wind, burning fuel debris may be lofted into the airstream, transported by local wind, and finally land on the surface of unburnt objects downwind, which may lead to the ignition of the objects contacted (Fig. 1). This phenomenon is called spotting. As observed by the on-site fire fighters, the embers formed in the fire sources, crossed the low fuel zone and a main road, flowed into the urban area and eventually ignited houses at various locations (Moran 2003). It has been found that pine needles, pieces of twigs or barks, often acted as embers during the fire (Livbom 2005).

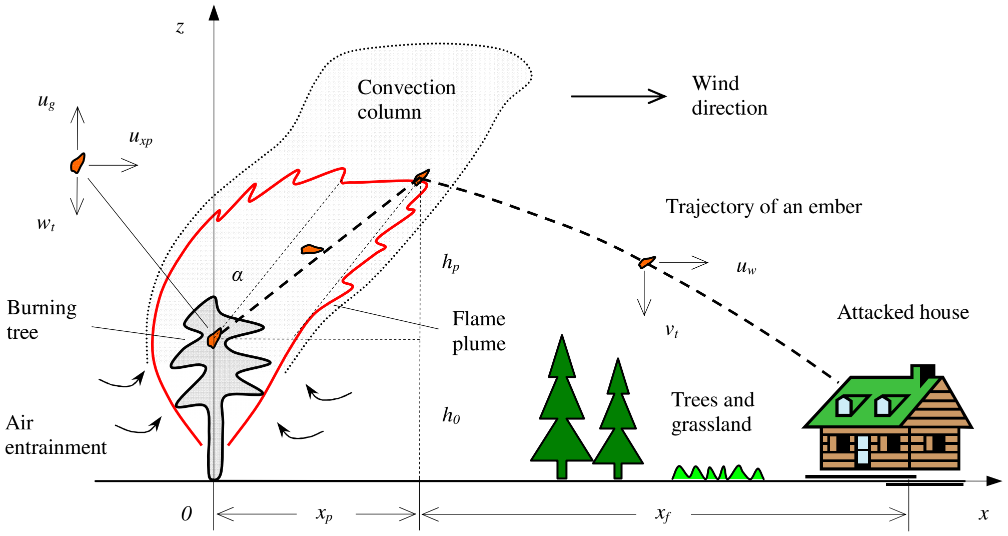

Fig. 1 An illustration of the generation of an ember and its trajectory during travel in the air stream.

Features of Transportation of Firebrands and the Associated Spot Fires

Using the model developed by Woycheese and co-workers (1999), the maximum loftable characteristic scale of the firebrands was evaluated and found to be between 20 and 40 mm under the determined range of the fuel consumption rate. Due to the presence of strong local wind, the embers would usually present as glowing rather than flaming (Tarifa *et al* 1965), as confirmed from the video taped by Moran (2003). Burning of an ember with such sizes may last from 3.5 to 14.6 min, in light of an empirical correlation, $t_b \approx d_0^2/(4\eta)$, where η is evaluated as 0.435 mm^2 s^{-1} from experimental data (Tarifa *et al* 1965).

The existing theory for the diffusion-controlled surface combustion of spherical firebrands also yields a relationship of proportionality of burnout time to the square of the diameter of a firebrand (Fu *et al* 1989, Woycheese *et al*

1999), however, the evaluated burnout times are much higher than those predicted using the empirical correlation, which should be attributed to the fact that during the model development the burning of a firebrand was only considered in a still environment rather than in a flow system (Woycheese *et al* 1999).

The up-loft of a firebrand is essentially driven by the drag force due to the buoyancy flow within the flame plume or the so-called convection column. Up-lofting gas velocity in the flame plume may be higher than 8.4 or 9.7 m/s under the current situations, evaluated by two independent methods (Muraszew 1974). Debris is lofted upwards but also drifts toward the edge of the flame plume due to the gas movement at the horizontal direction (Fig. 1). Once it reaches the maximum height at the plume boundary, the ember is then carried by local wind at a horizontal speed u_w and falls down at the same time at a mean fall velocity v_t (Albini 1979). The up-lofted height h_p is then determined by the following simplified correlation (Ellis 2000)

$$\frac{u_g - v_t}{u_w - 0.1u_g} = \frac{h_p}{d_c + h_p \tan\alpha}, \text{ i.e. } h_p = \frac{d_c\left(u_g - v_t\right)}{u_w - 0.1u_g - \left(u_g - v_t\right)\tan\alpha},$$

where d_c denotes the horizontal distance of a firebrand to the boundary of the flame plume and α stands for the flame tilt angle from the vertical. Parameter v_t is evaluated as 3.1, 4.3 or 4.4 m s^{-1}, respectively, corresponding to the mean terminal velocities of shortleaf, slash and loblolly pine needles during the free drop measurements in still air (Clements 1977). The travel distance downwind and the time spent for travel are then given by

$$x_{\min} = d_c + h_{p,\min}\tan\alpha + \left(h_0 + h_{p,\min}\right)\frac{u_w}{v_t} \text{ and } t_{\min} = \frac{h_{p,\min}}{u_{g,\min} - v_t} + \frac{h_0 + h_{p,\min}}{v_t}.$$

The model is good for estimating the minimum lofted height, travel distance and time spent for travel, by setting the lowest updraught gas flow rate in the flame plume, but only valid once an ember flying height does not exceed the flame height and the parameter u_g meets the requirement of $u_g\left(0.1 + \tan\alpha\right) < u_w + v_t \tan\alpha$. The simulated results of trajectories of firebrands under various situations are plotted in Fig. 2. Evidently, the minimum travel distance of a firebrand varies between 50 and 130 m in general.

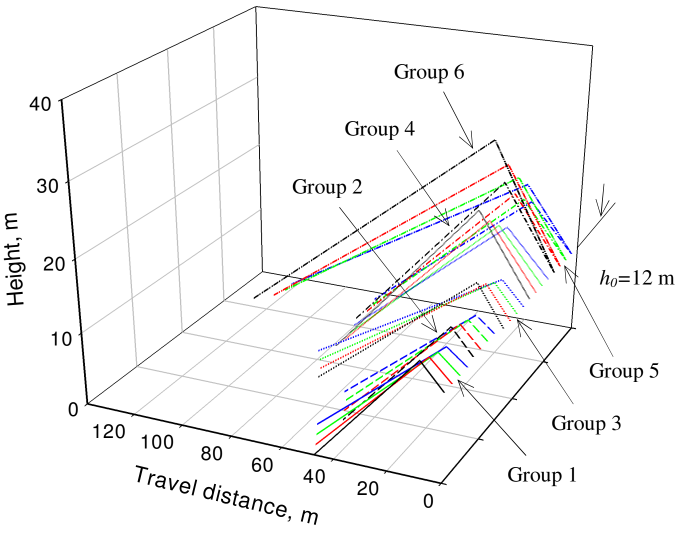

Fig. 2 Firebrand trajectories simulated at the conditions of wind speed at 40, 45, 50 and 55 km h^{-1}, respectively. Data of Groups 1 to 3 were calculated by setting d_c=6 m and u_g=8.4 m s^{-1} with v_t equal to 4.4, 4.3, and 3.1, respectively; Groups 4 to 6 were determined at d_c=12 m, u_g=9.7 m s^{-1} and the same typical values of v_t.

By solving the equations governing the motion of a cylindric firebrand in the flame plume and in the environmental air, a model was developed by Albini (1979) for predicting the maximum distance of a firebrand generated from crown fire and travelling over a flat terrain. Application of this model gives the maximum travel distance of between 130 and 400 m under the conditions of the wind speed varying from 40 to 55 km h^{-1} and the flame height of between 15 and 30 m (assumed heights of firebrands prior to leaving from the flame plumes). On the other hand, the maximum travel distance for a firebrand, predicted by the model of Woycheese *et al* (1999), is between 360 and 1350 m under the conditions of the fuel consumption rate of between 2.5 and 14 kg s^{-1} and the same range of wind speeds, which is larger than that estimated by the model of Albini (1979). The maximum travel distance of a firebrand could be over predicted by the model of Woycheese and co-workers (1999), since the wind effect on the structure of the buoyancy plume was not considered in the model development.

The estimated minimum and maximum travel distances downwind can be used to interpret the pattern of distribution of the affected houses in Duffy area. As shown in Fig. 3, the majority of the houses which sustained severe damage are located in the Γ-type band region, with the minimum distance to the edge of the plantations of ~50 m and the maximum of ~300 m, indicating the area that suffered from the most severe attack of embers. This observation coincides with the range of distances travelled by embers, determined using the simplified model and the model of Albini (1979). Evidence of the enormity of the ember attacks has been found during the post-fire survey in the region of the Duffy residential area that suffered most destruction (refer to Fig. 3) (Livbom 2005). The embers, such as pine needles, unidentified tree leaves, pieces of twigs and barks, in the size of less than a few centimetres, were spread on the roof, bricks beside window frames, ground in front of doors, and paved areas in backyard. Although embers definitely remain in the glowing status after travel across a distance of a few hundred meters, the landing of embers may not lead to the ignition of houses, depending on the energy carried by the individual embers and the combustibility of the objects contacted (Muraszew 1974). It has been often observed that as the result of ember attack, isolated burnt spots appeared on the house components and their surroundings, with the burnt areas falling into the range from 0.1 to 10,000 cm^2 (Livbom 2005). The discontinuous and irregular distribution of the affected houses in the Duffy area reflects the random feature of the landing of embers and the associated spot fires.

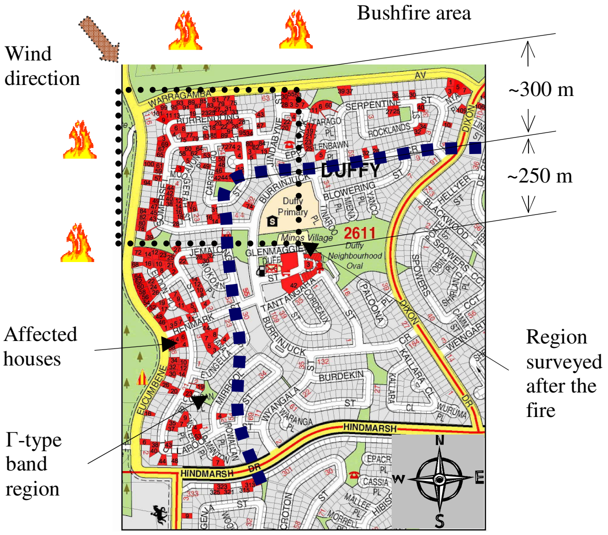

Fig. 3 Locations of the affected houses in Duffy area during ACT bushfire 2003 (Blanchi and Leonard 2005).

Once the high-intensity crown fire developed at the urban interface with the accompanying high-speed local wind, the phenomena of ember transport and the associated spot fires became dominant and very harmful to a broad area downwind. It seems that so far there are no appropriate tools available to mitigate this sort of hazard at the urban interface and protect the built environment under such circumstances.

Concluding Remarks

The burning of pine trees with accompanying of high-speed local wind resulted in the extreme fire behaviour at the Duffy urban interface. The crown fire presented in the pine tree vegetations, with the flame length of between 20 and 35 m, indicates the fireline intensity of between 21,000 and 48,000 kW m^{-1}. Such high-intensity crown fire generated considerable ember flow into the air stream, with the maximum size of the firebrands of ~40 mm. Calculations also show that the effective distance reached by the ember attack should be in the range of 50 and 400 m at the conditions of local wind speed varying from 40 to 55 km h^{-1}.

The Γ-type distribution of destructed houses in Duffy residential area is essentially the result of extensive attack of ember showers sourced from the bushfire at the urban interface, and the scatter in the locations of affected houses also represents the random feature of landing of embers and associated spot fires. The lesson of massive house destruction in severe bushfires suggests a great necessity in developing effective and efficient tools for protecting the built environment at the urban interface from the attack of bushfires, especially the embers generated.

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