The performance of a woven wire screen against firebrand showers under different wind speeds

Ahmad Sharifian[1], **Javad Hashempour**[2]

[1,2]*Computational Engineering and Science Research Centre (CESRC), School of Mechanical and Electrical Engineering, Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, Australia*

Abstract

This study is to assess the performance of a screen against leaf and mulch firebrand showers at different wind speeds. The experimental results show that there is a critical wind speed of approximately 9 m/s where a screen with openings of 1.61 mm and porosity of 54% becomes less effective in protecting a fuel bed at a distance of 4.48 m. The results show that the number of secondary glowing Eucalyptus populnea leaf firebrands behind the screen reach a maximum at a wind speed of approximately 12.7 m/s while that of hardwood mulch continuously increases for wind speeds up to 14.5 m/s.

Introduction

Risks associated with fires in Wildland–Urban Interface (WUI) areas are impacted by their rapid propagation mainly owing to fire radiation and severe firebrand attacks. A firebrand can fly metres or even kilometres ahead of a fire front and spread spot fires [1]. Previous studies have shown that firebrands are the main cause of house ignitions. Cohen [2] stated that firefighters are overwhelmed and fail to effectively contain the fires when firebrands fiercely attack and set several fires simultaneously. Firebrands can intrude into houses through openings [3] or windows broken by long exposure to excessive fire radiant heat flux [4]. Many construction codes and regulations in WUI areas mandate the application of wire screens to cover the openings of houses and buildings in order to minimise firebrand penetrations. These regulations offer different requirements for opening sizes of screens for different applications and are relatively inconsistent across countries.

Previous studies on the application of screens have explored the mechanisms of firebrand penetration through screens. Pioneer investigation on screens against firebrand attacks were carried out by Manzello et al [3] using NIST firebrand generator. They found that mulch firebrands could continue to burn after their arrival on a screen with openings of 1.5 mm at a wind speed of 9 m/s prior to fitting the opening size and subsequently could pass through the screen. Later, firebrand penetration was studied in both laboratory scale and full scale experiments using the NIST firebrand generator and the reduced scale Baby Dragon [5]. Similar to the previous study, firebrands kept burning and passing through the screens with opening sizes ranging from 1.04 mm to 5.34 mm at wind speeds ranging from 5 m/s to 7 m/s. In all the cases, such firebrands caused ignition of fuel beds located behind the screens at a distance of 19 cm. The study defined penetration ratio as the ratio of the number of firebrands at the leaving side of the screen to that of the approaching side. They found that the penetration ratio decreases as opening size decreases. A similar result was also reported in the test on a screen with openings of 6 mm by the Institute for Business and Home Safety (IBHS) [6] at wind speeds of 4 m/s to 6 m/s. Recently, the performance of wire screens against Eucalyptus populnea leaf firebrands were assessed at a wind speed of 14.5 m/s [7] using an improved version of the Baby Dragon capable of operating over a wide range of wind speeds [8]. It was found that these leaf firebrands break and generate smaller firebrands (secondary firebrands) when they hit screens with openings in the range of 0.99-11.15 mm at a wind speed of 14.5 m/s [7]. The authors defined the fragmentation ratio as the ratio of the number of leaving glowing firebrands to the number of approaching glowing firebrands. It was found that the fragmentation ratio could actually be greater than one due to shattering process which had not been reported in earlier studies. In another work, the same authors found that a screen with openings of 0.99 mm could efficiently protect a fuel bed at a distance of 4.48 m and a wind speed of 10 m/s [9]. The impact of wind speed on the flying distance of firebrands was shown both computationally [10,11,12] and experimentally [13], as well as demonstrating the wind speed impacts on firebrand burning rates [14], extinction time [15] and mass loss rate [16]. The combustion of firebrands has also been found to be related to the type of vegetation source [17]. In reality, the screens are likely to be exposed to a combination of different types of firebrands at various wind speeds.

This research aims to fill the gap in our understanding of the roles of vegetation type and wind speed on the capabilities of screens to protect a fuel bed behind these screens against firebrand shower. The two types of vegetation which were investigated in this work are Eucalyptus populnea leaf and hardwood mulch.

Methodology

The experimental arrangement consisted of an Ember Shower Simulator (ESS), a screen with a porosity of 54% and opening size of 1.61 mm (cell size of 2.18 mm and wire

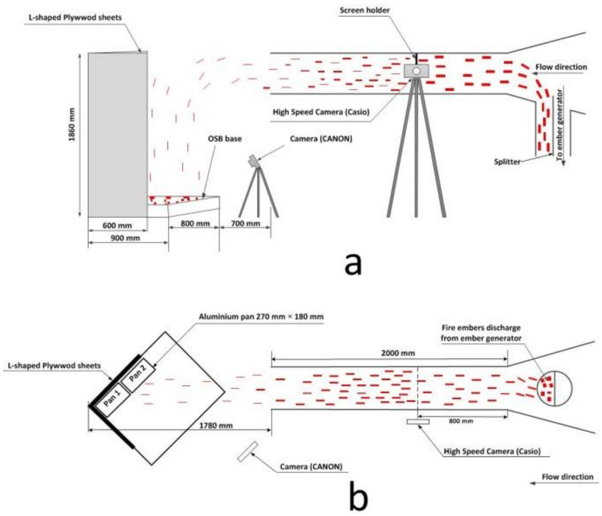

Figure 1 schematic of experiment layout including ESS and L-shape stand a) side view, b) top view.

diameter 0.57 mm), a stand to collect the leaving firebrands from the ESS and to direct them towards the fuel beds, two cotton fuel beds at an average distance of 4.48 m downstream of the screen, and two cameras. The range of wind speeds in the test section was from 6.5 m/s to 15.5 m/s.

The Ember Shower Simulator (ESS) consists of a fire ember generator and a wind tunnel (see figure 1a). The wind tunnel comprises a fan, an inlet duct, a contractor and a test section. The wind speed is regulated by moving the fan away from or towards the wind tunnel inlet. The air from the fan passes through the inlet section and the contractor before entering the test section. A vertical pipe with a diameter of 15 cm joins the fire ember generator to the wind tunnel at the middle bottom of the contractor. The pipe is split lengthwise into two equal parts by a metal sheet called a splitter (see figure 1), which is positioned perpendicular to the flow in the wind tunnel. The tip of the splitter is 5 cm above the contractor floor. Several flaps with different heights were manufactured to be mounted on the splitter and to direct a desired fraction of the air flow in the wind tunnel down into the entrance section of the pipe. The downward flow passes through both sections of the vertical pipe as well as the combustion chamber before re-entering the wind tunnel. Feeds are burnt inside the fire ember generator and the generated firebrands are driven upward by the flow and buoyancy force. The flow of the firebrands reenters the wind tunnel at the top of the vertical pipe. The feeds are ignited using an external source prior to running the fan. The square test section has a cross section of 20 cm × 20 cm. A fixed frame, denoted as the screen holder (figure 1), is located at a distance of 80 cm away from the inlet of the test section. The length of the test section is 200 cm. Preliminary investigation showed a maximum velocity non-uniformity of 9.5% at the inlet of the test section when the high flap of 150 mm is used. The maximum non-uniformity drops to 2.5% for a flap of 50 mm. More details on the performance of the ESS is available in [8].

The L-shaped stand was placed at the end of the wind tunnel to direct the firebrand shower onto two fuel beds (see figure 1), which were located at an average distance of 4.48 m from the screen holder. It was found that the arrangement could divert approximately 60% of the firebrands from the wind tunnel towards the fuel beds. The fuel beds were two aluminum pans (270 mm × 180 mm), filled with oven-dried cotton cloth, and placed horizontally on the ground next to the stand.

Two video cameras were deployed to monitor and record the experiments. The first camera was placed outside of the wind tunnel near the screen holder and could capture both sides of the screen holder in the same shot at a frame rate of 420 fps. The second camera was facing towards the fuel beds at a frame rate of 30 fps.

A MATLAB script was written to count the high number of glowing particles in the wind tunnel. The script counts the number of glowing firebrands passing through two virtual strips before and after the screen holder. The width and location of the strips have a major impact on the accuracy of counting when compared with manual counting. In practice, two strips with a width of 2 mm located 90 mm and 110 mm before and after the screen holder gave the best results with a maximum error of 5% for a representative sample of 500 firebrands. Reference [8] contains more details on the ESS and the visualisation and counting system used in this study.

Results and discussions

Eucalyptus populnea leaf firebrands

The first phase of experiments was carried out using 160 grams of dried Eucalyptus populnea leaves in the firebrand generator. The load was deliberately less than that of mulch vegetation to limit the flux of the generated firebrands which could cause significant error during the automated counting process. The experiments were performed at four wind speeds of 6.5 m/s, 9 m/s, 12.7 m/s and 15.5 m/s in the test section. The number of generated glowing firebrands counted at the inlet of the test section changed from a maximum of 23,450 at wind speed of 6.5 m/s to a minimum of 18,324 at a wind speed of 9 m/s (see Table 1). The duration of all experiments was 685 seconds but most leaf firebrands passed through the screen during the first half of the experiments.

Wind speed (m/s)/ Flap height	6.5 / 150mm	9 / 100mm	12.7 / 50mm	15.5 / no flap
Approaching glowing firebrands (N_i)	23,450	18,324	18,479	20,140
Leaving glowing firebrands (N_L)	43,450	40,204	63,222	38,022
Fragmentation ratio (N_L/N_i)	1.85	2.19	3.42	1.89
N_c	10	26	65	53
N_b	9	19	15	5
N_b/N_c (%)	90.0	73.1	23.1	9.4
Average wind speed on the fuel beds (m/s)	0.70	1.00	1.25	1.55

Table 1 Results for screen with 1.61 mm opening size in the test section and Eucalyptus leaf embers. N_c is the number of firebrands which came into contact with the fuel beds and N_b is the number of burnt spots on the fuel beds.

The results show that the fragmentation ratio increases as wind speed increases and reaches a peak before decreasing (see table 1). The fragmentation ratio was 1.85 at the wind speed of 6.5 m/s, 2.19 at the wind speed of 9 m/s, 3.42 at the wind speed of 12.7 m/s and then 1.89 at the wind speed of 15.5 m/s.

Two mechanisms of pausing and shattering during the passage of firebrands through screens were identified in a previous study [7]. The pausing mechanism acts to reduce the fragmentation ratio while the shattering mechanism acts to increase the ratio. The increase in the fragmentation ratio at wind speeds of up to 12.7 m/s shows that a higher wind speed corresponds to a shorter retention time for firebrands behind the screen and a higher number of secondary firebrands produced due to the shattering mechanism. It should be noted that the increase in the number of secondary firebrands means the decrease of their average size. The rise in the number of secondary firebrands was expected to continue at wind speeds higher than 12.7 m/s. However, the results showed that the fragmentation ratio decreases. This can be explained by taking into account the fact that the automated counting system is not able to count non-glowing firebrands. Therefore, the decrease of glowing secondary firebrands at the wind speed of 15.5 m/s does not imply a decrease in the total number of secondary firebrands. The main reason that can be attributed to the higher percentage of non-glowing firebrands at higher wind speeds is their shorter extinction time due to the higher wind speed [18] and their smaller size. In addition, it was observed that as wind speed increases, a larger fraction of secondary firebrands rotate or move erratically behind the screen. This can be related to the longer wake behind the screen and the lower momentum of smaller firebrands which traps them and gives them more time to extinguish before advancing to the virtual counting strip located 110 mm away from the screen.

Most Eucalyptus leaf firebrands extinguished before reaching the fuel beds or did not come into contact with them. The number of glowing Eucalyptus leaf firebrands which came into contact with the fuel beds (N_c) and the number of burnt spots on the fuel beds (N_b) are presented in table 1. The table includes the firebrand hazard ratio which is defined as the ratio of N_b/N_c. According to Table 1, the hazard ratio of Eucalyptus leaf firebrands on the cotton fuel beds at a distance of 4.48 m decreases as wind speed increases. At the wind speed of 6.5 m/s, the ratio is 90% but it decreases to 9.4% at the wind speed of 15.5 m/s. It should be noted that wind speed on the fuel beds is not quite constant (see table 1) and increases as the wind speed in the test section increases. This is not expected to have a major impact on the declining trend of the ratio. The decrease of the hazard ratio can be linked to the smaller size of the firebrands and their shorter extinction time at higher wind speeds.

From a practical point of view, perhaps the number of burnt spots on the fuel beds is more important than the hazard and fragmentation ratios. After counting the burnt spots on the two pans (see Table 1), it was found that N_b reached a maximum at a wind speed of 9 m/s. Therefore, it can be concluded that the positive impact of the screen with an opening of 1.61 mm in protection of cotton fuel beds at a distance of 4.48 m is greater at low and high wind speeds when compared with that at a wind speed of 9 m/s.

Hardwood mulch

The experiments were repeated for 0.5 kg hardwood mulch with the same screen and at wind speeds of 6.5 m/s, 9 m/s, 12.7 m/s and 14.5 m/s. The duration of the experiments was identical to the previous experiments and the firebrand flow was steadier than that of Eucalyptus populnea leaves.

Wind speed (m/s)/ Flap height	6.5 / 150 mm	9 / 100 mm	12.7 / 50 mm	14.5 / 50 mm
Approaching glowing firebrands (N_i)	8,980	11,234	6,877	17,453
Leaving glowing firebrands (N_L)	9,660	12,905	9,012	23,766
Fragmentation ratio (N_L/N_i)	1.08	1.15	1.31	1.36
N_c	106	314	NA	491
N_b	63	139	NA	62
N_b/N_c (%)	59.4	44.3	NA	12.6
Average wind speed on the fuel beds (m/s)	0.70	1.00	1.25	1.55

Table 2 Results for screen with 1.61 mm opening size in the test section and mulch firebrands. N_c is the number of firebrands which came into contact with the fuel beds and N_b is the number of burnt spots on the fuel beds.

Table 2 shows the number of the generated firebrands which greatly varied in the different experiments, even though conditions were kept as constant as possible. The wind speeds in the generator were maintained constant using the different flaps and the feed was selected from a well-mixed pile of mulch. The number was a minimum of 6,877 at the wind speed of 12.7 m/s and a maximum of 17,453 at the wind speed of 14.5 m/s. The results of the experiment at the wind speed of 12.7 m/s are not included in this article except for the calculation of the fragmentation ratio. The 6,877 glowing firebrands are still expected to yield a statistically reliable fragmentation ratio.

The results show that the fragmentation ratio increases as wind speed in the test section increases (see table 2 and figure 2). The reasons for the increase in the fragmentation ratio in this case are expected to be similar to those described for Eucalyptus leaf firebrands. Contrary to the Eucalyptus leaf firebrands, the ratio does not decrease with wind speed, but considering the declining rate of the increase (see figure 2), there might be a peak at a wind speed greater than 14.5 m/s. The lack of decline in the ratio for hardwood mulch can be attributed to their greater structural strength and extinction time as compared to Eucalyptus leaf firebrands. The fragmentation ratios of hardwood mulch are generally less than those of Eucalyptus leaf firebrands which is consistent with their greater strength. The observation also shows a lower percentage of secondary hardwood firebrands veering off their path due to the wake behind the screen which indicates their higher momentum and mass. Tables 1 and 2 show that a higher percentage of glowing hardwood firebrands survive the 4.48 m distance which supports their longer extinction time.

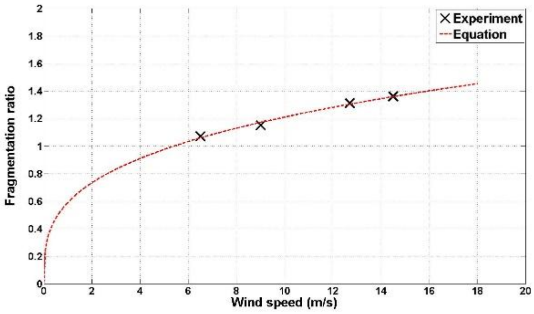

Figure 2 the change of fragmentation ratio versus wind speed for experiments with hardwood mulch firebrands and as estimated by equation.

Table 2 shows that the hazard ratio decreases from 59.4% at the wind speed of 6.5 m/s to 12.6% at the wind speed of 14.5 m/s. The decrease in the hazard ratio with the increase of wind speed can be linked to the smaller size of the firebrands and consequently to their shorter extinction time at higher wind speeds. As was expected, with one exception, the hazard ratios of hardwood firebrands are greater than those of Eucalyptus leaf firebrands (see Tables 1 and 2). In the case of the lowest wind speed (6.5 m/s in the test section and 0.7 m/s on the fuel beds) the hazard ratio of hardwood firebrands is 59.4% which is much less than the 90% determined for Eucalyptus leaf firebrands. The first possible explanation is that the number of glowing firebrands for Eucalyptus leaf firebrands (10) is not sufficient to draw a conclusion. There is another possible explanation which appears to be somewhat supported by viewing the videos. At the lowest wind speed, the size of hardwood firebrands are at their largest and combustion is the slowest among all cases. Therefore, some parts of the firebrand were not burning at the time of contact with the fuel beds. It is quite possible that a considerable fraction of hardwood mulch hit the fuel beds on the unburnt side. If this explanation is correct, a higher hazard ratio of hardwood firebrands than that of Eucalyptus leaf firebrands

Figure 3 burnt points on cotton in pan 1 in experiments with mulch firebrands at wind speed of a) 6.5m/s, b) 9m/s, c) 14.5m/s.

should be expected at a longer distance. This possibility requires further investigation and was not addressed in the present study.

It is interesting to note that, similar to the leaf firebrands, the number of burnt spots on the fuel beds reached a maximum at the wind speed of 9 m/s (see table 2 and figure 3). This can be explained by considering the high number of burnt spots on the fuel beds (139) to those at 6.5 m/s (63) and 14.5 m/s (62) as well as the higher hazard ratio (44.3%) compared to that at 14.5 m/s (12.6%). The reasons for the increase in the number of firebrands on the fuel beds and the decrease of the hazard ratio with wind speed have already been covered.

Conclusions

The performance of a screen with openings of 1.61 mm in protecting cotton fuel beds located 4.48 m downstream against the Eucalyptus populnea leaf firebrand shower is lowest at a wind speed of 9 m/s. The performance improves at wind speeds lower than 9 m/s due to the decrease in the fragmentation ratio, and improves at higher wind speeds due to the decrease in the size of secondary firebrands and their extinction time, and the increase in turbulence intensity in wakes behind the screen. For the same conditions described above, the wind speed of 9 m/s was also found to be the critical value in the case of the hardwood mulch firebrand shower. At a slower wind speed in the test section, the fragmentation ratio decreases, indicating an improvement in screen performance. The results show that, despite the increase in the fragmentation ratio at wind speeds higher than the critical value, the performance of the screen in protecting the fuel bed improves due to the smaller sizes of secondary firebrands. The results also imply that there might be a maximum fragmentation ratio in the case of hardwood mulch firebrands at a wind speed greater than 14.5 m/s. The main conclusion of this article is that wind speed is an important factor in the evaluation of the performance of screens against firebrand shower and thus this requires more attention in developing relevant guidelines and standards.

References

[1] R. W. Wells, *Fire at Peshtigo*. Prentice Hall, 1968.

[2] J. D. Cohen, “The wildland-urban interface fire problem,” *Fremontia*, vol. 38, no. 2, pp. 16–22, 2010.

[3] S. Manzello, J. Shields, J. Yang, Y. Hayashi, and D. Nii, “On the use of a firebrand generator to investigate the ignition of structures in wildland–urban interface (WUI) fires,” in *INTERFLAM*, 2007, pp. 3–5.

[4] C. Ramsay, L. S. Rudolph, and L. Rudolph, *Landscape and building design for bushfire areas*. CSIRO Publishing, 2003.

[5] S. L. Manzello, S.-H. Park, S. Suzuki, J. R. Shields, and Y. Hayashi, “Experimental investigation of structure vulnerabilities to firebrand showers,” *Fire Saf. J.*, vol. 46, no. 8, pp. 568–578, Nov. 2011.

[6] Stephen L. Quarles, “Vulnerabilities of buildings to wildfire exposures,” *extension*, 2012.Available at: http://www.extension.org/pages/63495/vulnerabilities-of-buildings-to-wildfire-exposures#.VPeXW_mUeQB

[7] J. Hashempour and A. Sharifian, “Effective factors on the performance of woven wire screens against leaf firebrand attacks,” *J. Fire Sci.*, Under review, Jul. 2016.

[8] A. Sharifian and J. Hashempour, “A novel ember shower simulator for assessing performance of low porosity screens at high wind speeds against firebrand attacks,” *J. Fire Sci.*, vol.34, no. 4, pp.335-355, Jul. 2016

[9] A. Sharifian and J. Hashempour, “The combined effects of woven wire screens and buffer zone in mitigating risk asscoaited with firebrand showers,” *Fire Saf. J.*, Under review, Dec. 2015.

[10] R. A. Anthenien, S. D. Tse, and A. Carlos Fernandez-Pello, “On the trajectories of embers initially elevated or lofted by small scale ground fire plumes in high winds,” *Fire Saf. J.*, vol. 41, no. 5, pp. 349–363, Jul. 2006.

[11] L. A. Oliveira, A. G. Lopes, B. R. Baliga, M. Almeida, and D. X. Viegas, “Numerical prediction of size, mass, temperature and trajectory of cylindrical wind-driven firebrands,” *Int. J. Wildl. Fire*, vol. 23, no. 5, pp. 698–708, 2014.

[12] N. Sardoy, J. L. Consalvi, A. Kaiss, A. C. Fernandez-Pello, and B. Porterie, “Numerical study of ground-level distribution of firebrands generated by line fires,” *Combust. Flame*, vol. 154, no. 3, pp. 478–488, Aug. 2008.

[13] S. L. Manzello, J. R. Shields, T. G. Cleary, A. Maranghides, W. E. Mell, J. C. Yang, Y. Hayashi, D. Nii, and T. Kurita, “On the development and characterization of a firebrand generator,” *Fire Saf. J.*, vol. 43, no. 4, pp. 258–268, May 2008.

[14] S. Bhutia, M. A. Jenkins, and R. Sun, “Comparison of firebrand propagation prediction by a plume model and a coupled–fire/atmosphere large–eddy simulator,” *J. Adv. Model. Earth Syst.*, vol. 2, p. 4, Mar. 2010.

[15] C. S. Tarifa, P. P. del Notario, and F. G. Moreno, “On the flight paths and lifetimes of burning particles of wood,” *Symp. Combust.*, vol. 10, no. 1, pp. 1021–1037, Jan. 1965.

[16] M. Almeida, D. X. Viegas, and A. I. Miranda, “Combustion of eucalyptus bark firebrands in varying flow incidence and velocity conditions,” *Int. J. Wildl. Fire*, vol. 22, no. 7, p. 980, 2013.

[17] A. Ganteaume, M. Guijarro, M. Jappiot, C. Hernando, C. Lampin-Maillet, P. Pérez-Gorostiaga, and J. A. Vega, “Laboratory characterization of firebrands involved in spot fires,” *Ann. For. Sci.*, vol. 68, no. 3, pp. 531–541, Apr. 2011.

[18] V. Babrauskas, *Ignition handbook: Principles and applications to fire safety engineering, fire investigation, risk management and forensic science*, Illustrate. Fire Science Publishers, 2003.