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On the development and characterization of a firebrand generator

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Abstract

A unique experimental apparatus has been constructed in order to generate a controlled and repeatable size and mass distribution of glowing firebrands. The present study reports on a series of experiments conducted in order to characterize the performance of this firebrand generator. Firebrand generator characterization experiments were performed at the Fire Research Wind Tunnel Facility (FRWTF) at the Building Research Institute (BRI) in Tsukuba, Japan. The firebrand generator was fed with three different initial firebrand geometries, two different sized cylinders and one size of disks. Cylinders were used to simulate firebrand fluxes from vegetation, such as trees, while disks were used to simulate a firebrand flux from burning structures. Samples of these geometries were constructed from wood dowels, fed into the firebrand generator, ignited, and the glowing firebrands generated were collected using an array of water filled pans. The pans were filled with water in order to quench combustion. The collected firebrands were subsequently dried and the size and mass distribution was measured. These experiments were performed over a range of wind tunnel speeds, with no wind speed present to 9 m/s, to determine the lofting distance of the firebrands generated. Finally, the size and mass distribution produced from the firebrand generator are compared to those produced from burning trees. Results of the study are presented and discussed.

Keywords: Firebrands; WUI fires

1. Introduction

Firebrands are produced as trees and other objects burn in wildland–urban interface (WUI) fires. Understanding how these hot firebrands can ignite surrounding fuel beds is an important consideration in mitigating fire spread in communities. Ignition due to spotting is one of the most difficult aspects to understand in these fires [1,2].

Due to the sheer complexity involved, it is useful to delineate the firebrand problem into three main areas: the generation from vegetation and structures, subsequent transport through the atmosphere, and the ultimate ignition of fuels after firebrand impingement. Most firebrand studies, experimental and numerical, have focused on firebrand transport [3–11]. Experimental investigations have been preformed to determine burning rates and drag of simulated firebrands (wood pieces of different geometries) to estimate the maximum lofting distances [6,7]. The burning properties of simulated firebrands have been used to develop models to perform transport calculations [3,6]. The main objective of firebrand transport studies is to determine the potential spotting distance of firebrands [5,8,9].

Unfortunately, a limited number of studies have been performed investigating firebrand generation from vegetation and structures [12–14] and the ultimate ignition of materials due to firebrand attack [15–19]. Waterman [12] burned full-scale segments of different roof assemblies and the firebrands produced were trapped by a screened chamber and fell into a quenching pool; the firebrands collected were generally disk shaped. Recently, Manzello et al. [13,14] have determined the size and mass distribution of firebrands produced from burning trees. Manzello et al. [18,19] have also conducted experiments investigating the

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ignition of fuel beds to firebrand attack. The general lack of knowledge of the type of firebrands that are produced as well as the type of materials that may be ignited has greatly hampered further understanding of this problem.

A pragmatic approach to mitigate firebrand ignition of structures in WUI fires is to design homes that are more resistant to firebrand ignition. Building codes and standards are needed to guide construction of new structures in areas known to be prone to WUI fires in order to mitigate structural ignition in the event of a firebrand attack [2]. To the authors' knowledge, no experimental methods are presently available to generate a controlled flux of firebrands on a large scale (as opposed to the small, laboratory scale experiments described above) and direct this firebrand flux onto structural elements to ascertain their resistance to ignition as a part of a full-scale structural system.

To this end, an experimental apparatus has been constructed in order to generate a controlled and repeatable size and mass distribution of glowing firebrands. The effort described is part of an international collaboration established between the National Institute of Standards and Technology (NIST) in the USA, and the Building Research Institute (BRI) in Japan to quantify firebrand production from vegetation and firebrand ignition of structures.

The firebrand generator was fed with three different initial firebrand geometries. Samples of these geometries were constructed from wood dowels, fed into the firebrand generator, ignited, and the glowing firebrands generated were collected in an array of water filled pans that were arranged to collect the bulk of the lofted firebrands; the arrangement was determined from repeated preliminary studies. These experiments were performed over a range of wind speeds to determine the lofting distance of the firebrands generated. Finally, the size and mass distribution produced from the firebrand generator are compared to those produced from burning trees.

2. Experimental description

Fig. 1 is a drawing of the experimental apparatus. The top panel displays the procedure detailing the methodology for loading the simulated firebrands into the apparatus. The wood pieces are deposited into the firebrand generator by removing the top portion. During the loading process, careful attention was paid to make sure that the layer of firebrands was uniform in height; the firebrands were not concentrated on one side. The orientation of samples inside the device was random. The bottom panel displays the device completely constructed. The wood pieces were supported using a stainless steel mesh screen (0.35 cm spacing), which was carefully selected. Two different cylinder sizes were used. The first geometry was cylinders 8 mm in diameter and 50 mm in length; the second geometry was cylinders 12.5 mm in diameter and 50 mm in length. Experimental work conducted by Manzello et al. [13,14] to determine the size and mass distribution of firebrands generated from vegetation (specifically trees) was used to select this size range of cylinders. One size class of disk-shaped wood was used; 25 mm in diameter and 6 mm in length. Disk-shaped brands are known to be formed when structures burn, hence the reason for selecting this type of geometry [12]. A total of 700 g was used as the initial mass for each of the geometries utilized in the experiments.

All of the wood pieces used for the experiments were obtained as dowels (Ponderosa Pine) and cut down to the appropriate sizes. Ponderosa Pine wood was used as the wood type for these experiments since it was available machined in 3-m-long dowels. This greatly reduced the cost of machining the sheer number of cylinders and disks needed for the experiments. In addition, Ponderosa Pine trees are abundant in the Western United States, a location where many WUI fires have occurred in the USA. Thus, it is reasonable to expect that this type of wood would be a source of firebrands. The average moisture content of all wood pieces used at ignition was 11% (dry basis). The moisture content was determined by oven drying the samples. It was found that 3 h of oven drying at 104 °C was sufficient to remove all the moisture in the wood pieces used for the experiments. The disks and cylinders were metered out by mass and then stored in plastic containers prior to conducting each experiment. Control of the moisture was very important to guarantee repeatable experiments.

The firebrand generator was driven by a 1.5 kW blower (Cincinnati Fan Model PB-12A) that was powered by a gasoline electrical generator. The maximum mass flow rate that could be obtained from the blower was 560 g/s. The gasoline electric generator provided the blower with the necessary power requirements (see Fig. 1). These power requirements were not available at the Fire Research Wind Tunnel Facility (FRWTF), necessitating the use of a portable power source. Furthermore, the firebrand generator was designed to be fully portable in order to test ignition of any structure or structural element.

The experiments were conducted in the following manner. After the wood pieces of a given geometry were loaded, the top section of the firebrand generator was coupled to the main body of the apparatus (see Fig. 1). With the exception of the flexible hose, all components of the apparatus were constructed from galvanized steel sections (0.8 mm in thickness). The blower was then switched on to provide a low flow for ignition (5 Hz fan speed corresponds to 1.0 m/s flow inside the duct measured upstream of the wood pieces). The two propane burners (Benzomatic Pencil Flame Torch Model JT681) were then ignited individually and simultaneously inserted into the side of the generator. Each burner was connected to a 0.635 cm diameter copper tube with the propane regulator; this configuration allowed for a 1.3 cm flame length from each burner and the propane mass flow rate was measured as 0.1 g/s. The wood pieces were ignited for a total time of 45 s. After 45 s of ignition, the fan speed of the blower was increased (12 Hz fan speed corresponds to 2.0 m/s flow inside the duct measured upstream of the wood

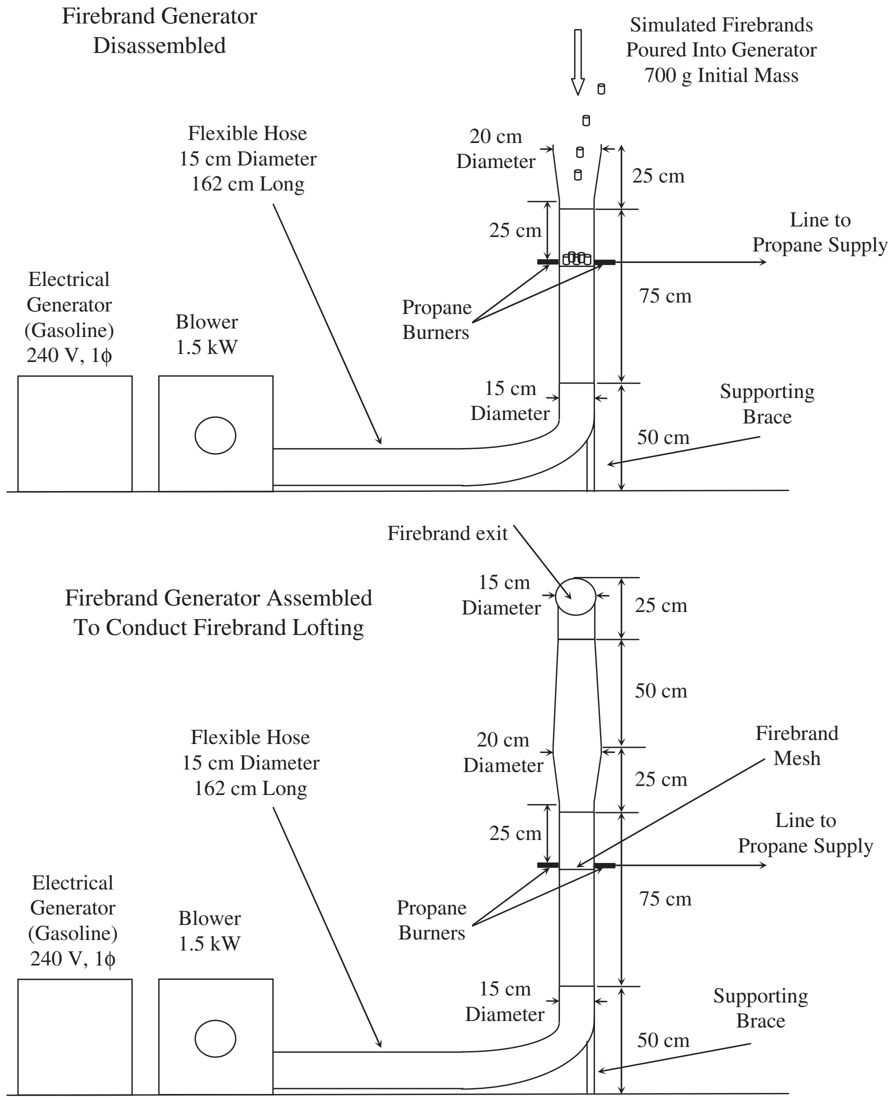

Fig. 1. Schematic of firebrand generator, the loading process is displayed.

pieces). The burners were subsequently switched off at 90 s after ignition. This sequence of events was selected in order to generate a continuous flux of glowing firebrands for approximately 2 min duration.

The vertical velocity inside the firebrand generator was not the same for the different geometries used. Although the flow provided upstream of the firebrand bed was the same, the pressure drop was different across the bed of firebrands loaded into the generator for the two different cylindrical shapes used. The reason for this was that the mass was fixed for each size class. Therefore, more firebrands of 8 mm diameter and 50 mm in length were required to reach the 700 g requirements. Accordingly, the vertical velocity downstream of the firebrand bed was different for the two cylindrical cases; the velocity was actually lower for the smaller diameter sized cylinders.

The principle behind the operation of the apparatus was simple; after ignition, the wood pieces begin to burn and the density decreased until which point the low air flow passing through the support mesh was able to loft and exit the device as firebrands at low velocity. The timing and fan blower speed timing is not random; if a higher fan speed of the blower was selected, the firebrands produced would be forced out of the exit earlier, resulting in flaming firebrands, which was not desired in this phase of characterization.

The firebrand generator was installed inside the test section of the FRWTF at BRI. A schematic of the facility is displayed in Fig. 2a. The facility was equipped with 4.0 m fan used to produce the wind field and was capable of producing up to a 10 m/s wind flow. The location of the firebrand generator is shown. To track the evolution of the size and mass distribution of firebrands produced, a series of water pans was placed downstream of the firebrand generator (see Fig. 2b). A total of 157 rectangular pans (water-filled) were used to collect firebrands. Each pan was 49.5 cm long and 29.5 cm wide. The arrangement and width of the pans was not random; rather it was based on scoping experiments to determine the locations where the firebrands would most likely land.

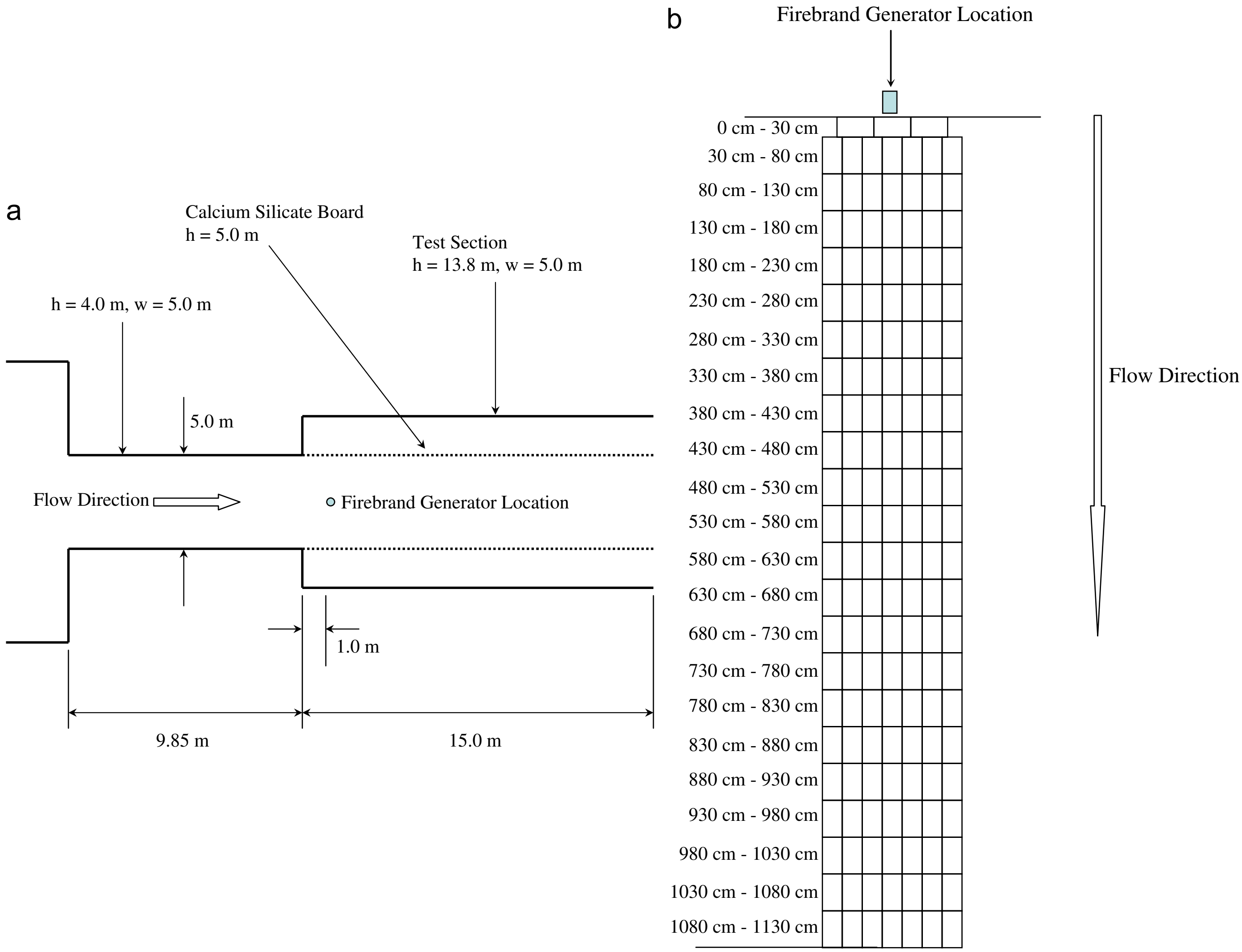

Fig. 2. (a) Schematic of the FRWTF. (b) Layout of pans used to collect the firebrands produced from the generator.

After the experiments were completed, the pans were collected and the firebrands were filtered from the water using a series of fine mesh filters. The firebrands were subsequently dried in an oven held at 104 °C for 8 h. A digital photograph (Fig. 3) shows typical firebrands produced using cylinders 8 mm in diameter and 50 mm in length. For each of the firebrands collected, the firebrand diameter was determined by averaging the thinnest cross-section of the firebrand to that of the thickest cross-section of the firebrand. The firebrand sizes were then measured using precision calipers (1/100 mm resolution). Following size determination, the firebrands were then weighed using a precision balance (0.001 g resolution). For each experiment conducted, more than 100 firebrands were dried and measured. In all, more than 3000 collected firebrands were sized and weighed.

Fig. 3. Digital photograph showing typical firebrands collected when 8 mm diameter, 50 mm long cylinders were used.

3. Results and discussion

The first series of experiments conducted was to determine the size and mass distribution of the firebrands produced from the apparatus at baseline wind conditions, i.e. no wind speed present. Fig. 4a and b displays the mass distributions obtained for cylinders 8 mm diameter and

50 mm in length, and cylinders 12.5 mm in diameter and 50 mm in length, respectively. Fig. 4c displays the mass distribution obtained for disks 25 mm in diameter and 6 mm in length. Three experiments were performed for each of the geometries tested. Each distribution was repeatable; for brevity the results of one of the three tests are selected and displayed in the figures.

The average total mass of firebrands collected was 57 g (varied from 50 to 64 g) for cylinders 8 mm diameter and 50 mm in length. With regard to cylinders 12.5 mm diameter and 50 mm in length, the total average mass of firebrands collected was 43 g (varied from 38 to 48 g). Finally, the average total mass of firebrands was 44 g (varied from 37 to 51 g) when the input geometry was disks

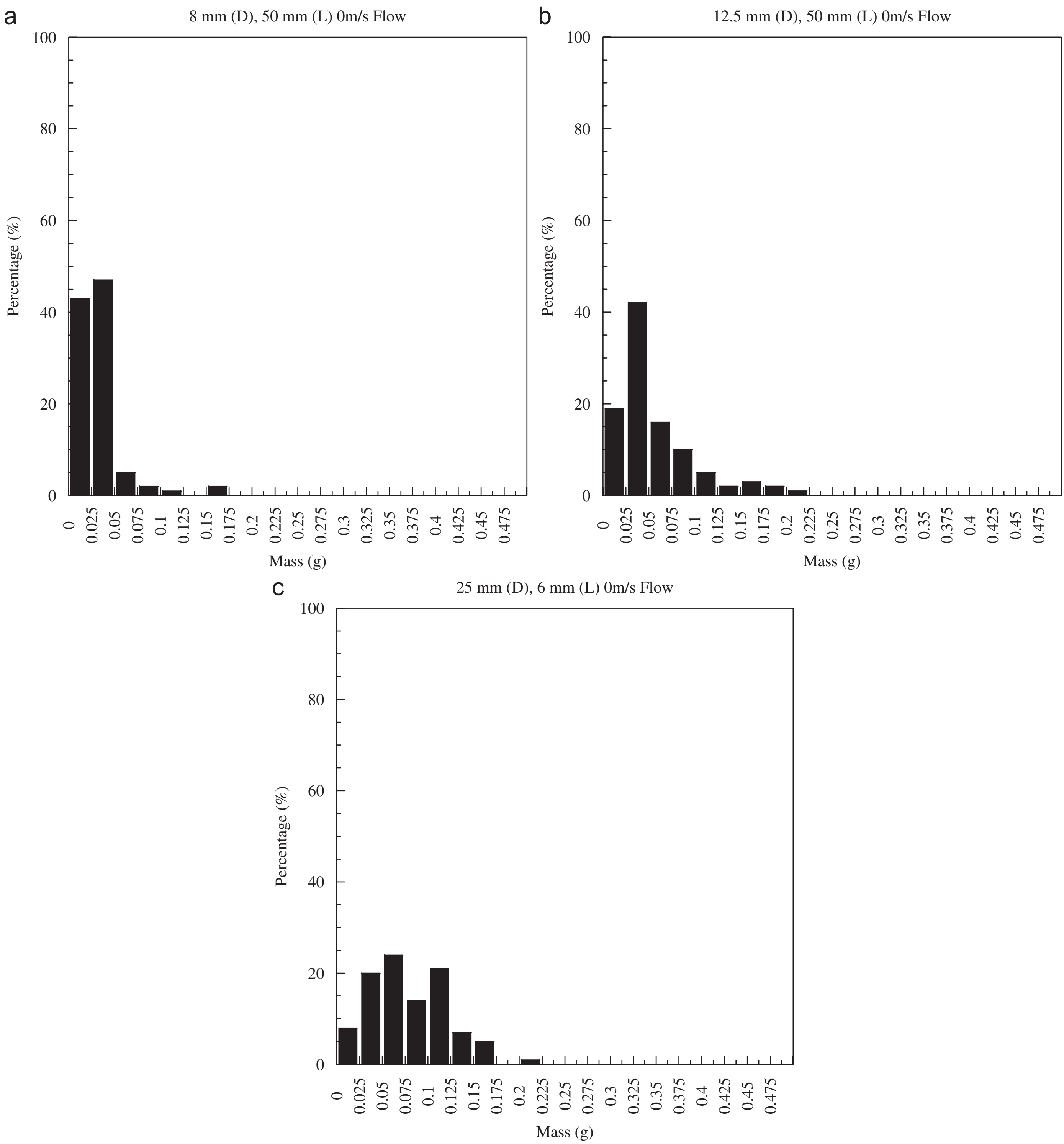

Fig. 4. (a) Baseline firebrand mass distribution for 8 mm diameter, 50 mm long cylinders. (b) Baseline firebrand mass distribution for 12.5 mm diameter, 50 mm long cylinders. (c) Baseline firebrand mass distribution for 25 mm diameter, 6 mm long disks.

25 mm diameter and 6 mm in length. The total mass was an important parameter to characterize in order to verify the repeatability of the experiments. Under no wind conditions, all of the firebrands generated are collected at the pan locations. To ensure this, scoping experiments were performed and the landing locations of the firebrands generated were imaged from several vantage points; this information was then used for selection of the pan locations. As the wind speed was subsequently increased, the total mass collected during cases of no wind versus

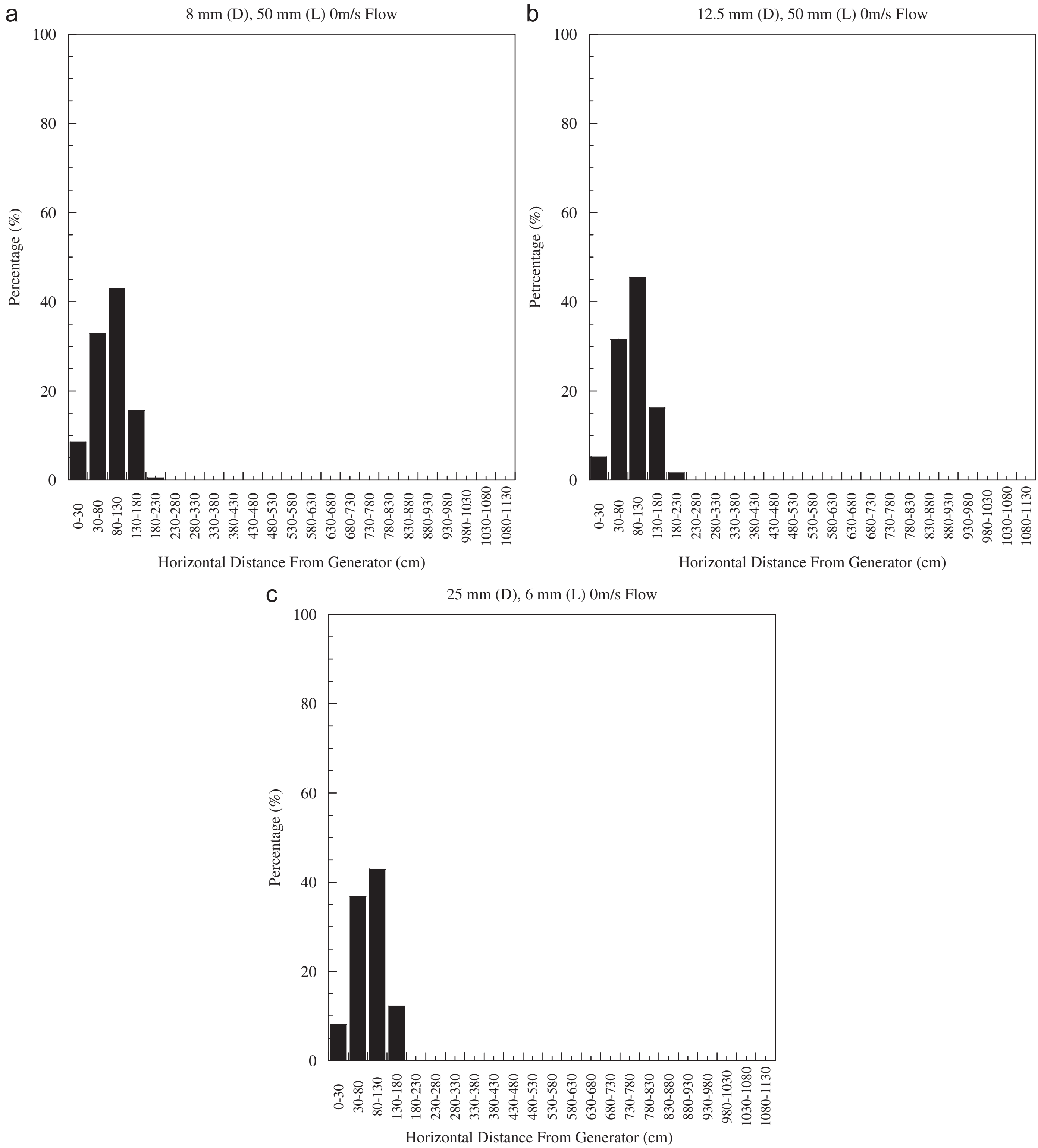

Fig. 5. (a) Baseline firebrand spatial distribution for 8 mm diameter, 50 mm long cylinders. (b) Baseline firebrand spatial distribution for 12.5 mm diameter, 50 mm long cylinders. (c) Baseline firebrand spatial distribution for 25 mm diameter, 6 mm long disks.

cases with wind were used to determine the percentage of firebrands that were not able to be captured using the array of pans.

For the experiments that used cylinders as the initial geometry, it was observed that cylindrical firebrands were produced by the generator. The average size of the firebrands produced was 5.6 mm in diameter (varied from 4.8 to 6.4 mm) and 13.5 mm in length (varied from 6.5 to 20.5 mm) for wood cylinders initially 8 mm diameter and 50 mm in length. The wood cylinders initially 12.5 mm in

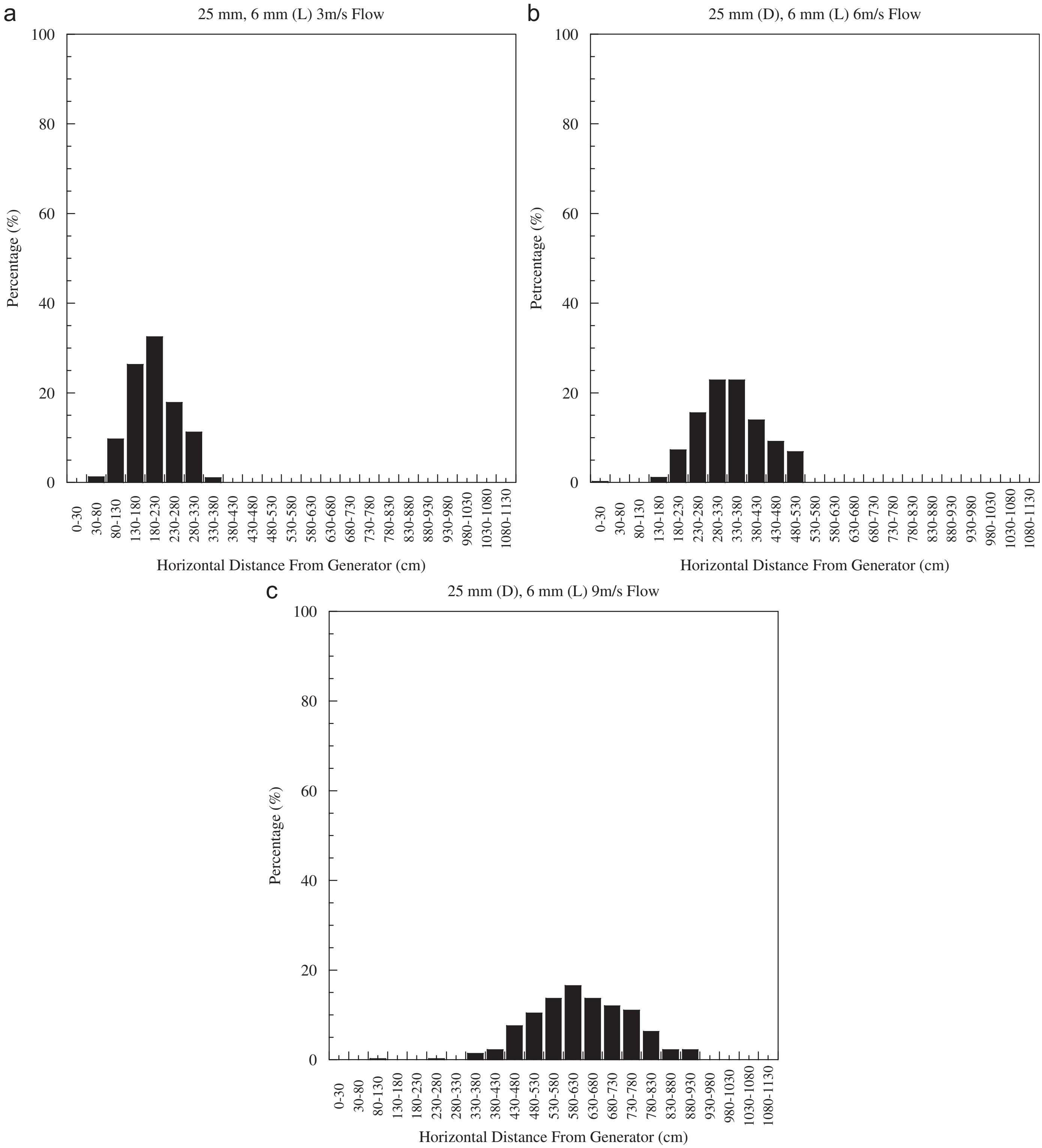

Fig. 6. Evolution of the firebrand spatial distribution as a function of applied wind speed. Data are shown for the disk geometry only: (a) 3 m/s wind speed, (b) 6 m/s wind speed and (c) 9 m/s wind speed.

diameter and 50 mm in length, produced firebrands 7.2 mm in diameter (varied from 5.4 to 9 mm) and 12.2 mm in length (varied from 6.4 to 18 mm).

When disks were used, the output size distribution was more difficult to characterize. It was observed that for all the three experiments under no wind, the percentage of the firebrands generated as disks was only 8% of the total mass produced. Thus, disks were observed to fragment; most of the firebrands generated broke up and produced a series of half-disk shapes. In these experiments, the grain orientation was perpendicular to the surface of the disk. Future work will investigate the influence of this parameter on the firebrands produced. Of the disks remaining, the average diameter was 16 mm (varied from 14 to 18 mm) and 5 mm in length (varied from 4 to 6 mm). For the remaining half disk shapes, the average diameter was 14 mm (varied from 10 to 18 mm) and 5 mm in length (varied from 3 to 7 mm).

Figs. 5a–c displays the spatially resolved locations where the firebrands landed under no flow conditions. In Figs. 5–7, the percentage shown on the *y*-axis corresponds to the percentage of the total number of firebrands counted at each spatial location. This was determined by taking high resolution digital photographs of the pans at each spatial location and counting the number of firebrands in the pans. As can be seen from the figures, the peak of the firebrand distribution occurred at pan locations 80–130 cm from the exit of the generator, independent of initial geometry used. After the baseline (no wind) distributions were determined, the wind speed was varied to investigate the lofting capability of the firebrands produced. The wind speed was verified using an array of hot wire anemometers. These results are displayed in Figs. 6a–c for firebrands produced from disk shaped pieces. As can be seen from the figure, the lofting distance increased as the wind speed was increased, which was to be expected. Fig. 7 displays the spatial distribution of the remaining geometries used at 9 m/s. At 9 m/s, each of the geometries tested resulted in the largest percentage of the number of firebrands lofted in the range of 580–630 cm (horizontal distance) from the generator. These detailed findings regarding firebrand lofting may be used to validate a model of firebrand transport.

The total mass was also measured for each of the geometries tested as function of wind speed. For cylinders, it was observed that 80% and 60% of the mass (as compared to baseline, no wind conditions) was recovered at 9 m/s in the pans for 8 mm diameter, 50 mm long, and 12.5 mm diameter, 50 mm long cylinders, respectively. For disks, 60% of the mass (as compared to baseline, no wind conditions) was recovered. The width of the pans was arranged very carefully, based on scoping experiments that were conducted to image locations where the firebrands would land. Therefore, the possibility of the firebrands landing outside the width of the pan locations was not likely. From video records, a significant number of firebrands were lofted outside the measurement location (downstream) at 9 m/s. In addition, it is possible that several firebrands were also burned completely before reaching the pans at the higher velocities. Therefore, the reduction in mass at 9 m/s was due to a combination of these effects.

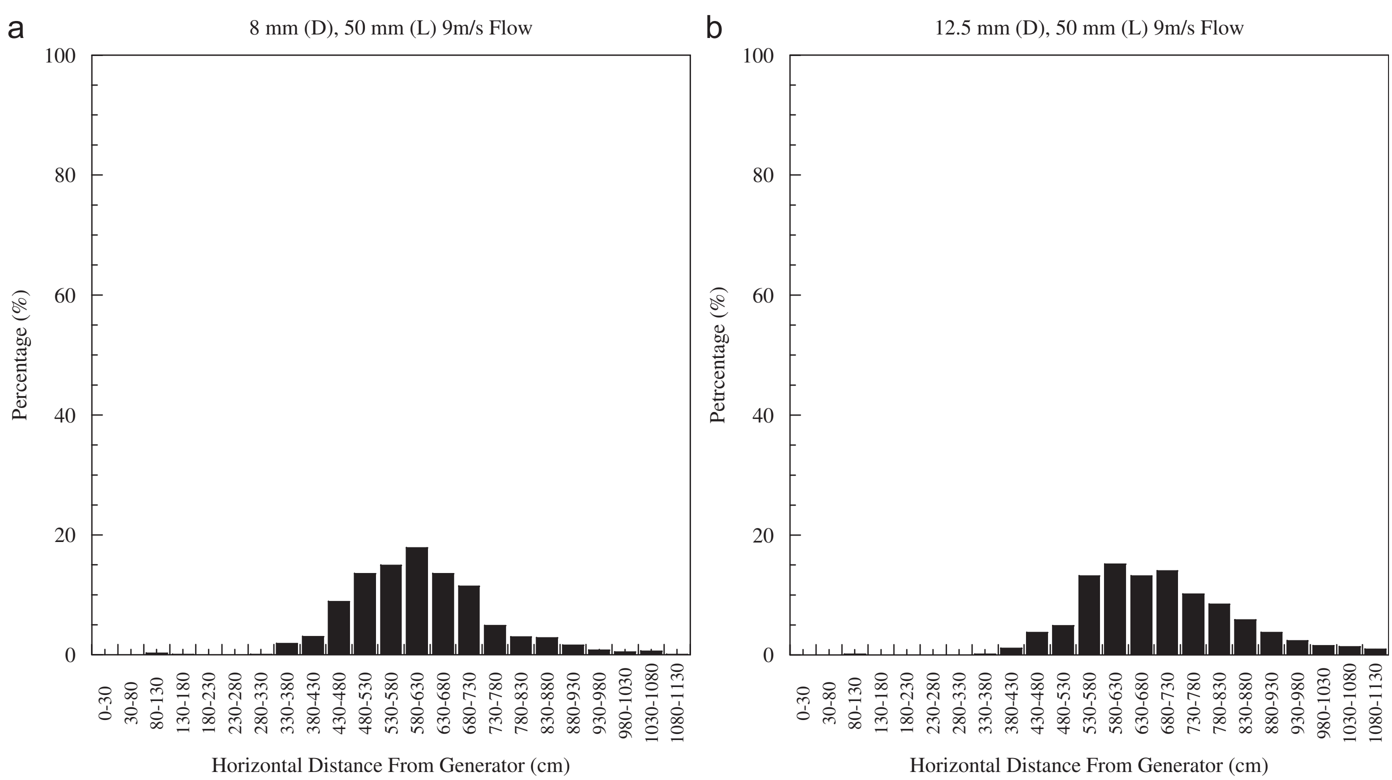

Fig. 7. Firebrand spatial distribution at 9 m/s: (a) 8 mm diameter, 50 mm long cylinders and (b) 12.5 mm diameter, 50 mm long cylinders.

As was mentioned previously, experimental work conducted by Manzello et al. [13,14] to determine the size and mass distribution of firebrands generated from vegetation, specifically trees, was used to select the initial size range of cylinders in this study. In that work, an array of pans filled with water was used to collect the firebrands that were generated from the burning trees. The firebrands were subsequently dried and the sizes were measured using calipers and the dry mass was determined using a precision balance. Based on the results of two different tree species of varying crown height and moisture content (Douglas-Fir Trees and Korean Pine Trees) burning singly under no wind, cylindrical firebrands were observed to be produced. The moisture content of the tree samples was measured using a Computrac[1] moisture meter. Needle samples as well as small branch samples (three heights, four radial locations at each height) were collected for the moisture measurements. The uncertainty in these measurements is estimated to be $\pm 10\%$. The uncertainty in the tree moisture content is dependent upon the spatial variability within the tree as well as the uncertainty of the analyzer used. Further details regarding the tree burning experiments have been provided elsewhere [13,14].

It is worthwhile to compare the size and mass distribution of firebrands produced using the firebrand generator to those measured by trees [13,14]. Fig. 8a displays the firebrand surface area distribution (calculated assuming cylindrical geometry) as a function of firebrand mass for firebrands collected from Douglas-Fir trees as well as Korean Pine trees under similar moisture content. Based on a comparison of only two tree species completed to date, Manzello et al. [13,14] reported that cylindrical firebrands were produced as the trees burned. In those investigations, the trees that were tested were up to 5 m in height and hence were relatively young trees [13,14]. However, it is plausible that different tree species may produce different types (other than cylinders) of firebrands. In addition, trees with different bark characteristics may also produce different firebrands (e.g. Eucalyptus tree). Fig. 8b displays the same analysis performed for the firebrands collected using the firebrand generator, based on the two different cylinder sizes fed into the apparatus. The firebrand generator accurately represented the range of firebrands produced up to the mass class of 0.2 g (see Fig. 9 for detail). Beyond this, differences were observed between those firebrands produced by the apparatus to those produced by the burning of trees; the apparatus did not produce firebrands larger than 0.2 g. The result was due the range of input conditions.

Finally, when comparing the total firebrand mass produced using the firebrand generator to the total mass of firebrands produced from tree burns, the firebrand generator has the ability to produce a total mass of

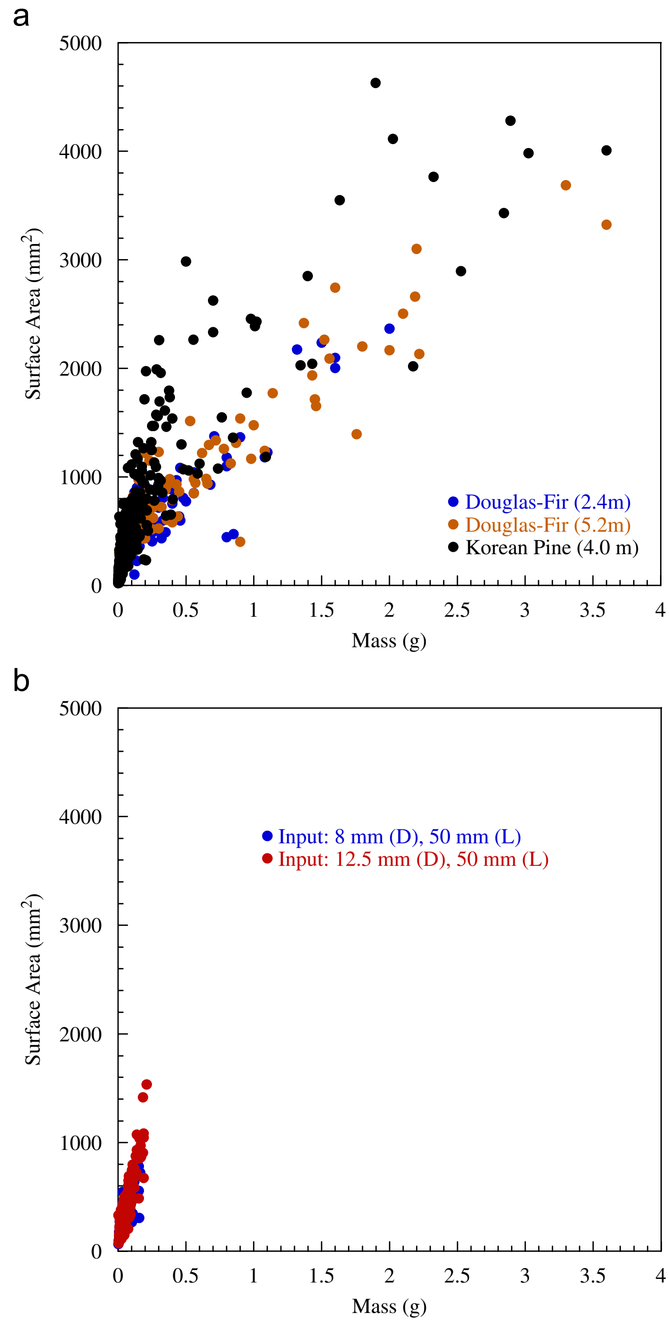

Fig. 8. (a) Calculated surface area plotted as a function of mass for firebrands produced from burning trees. (b) Calculated surface area plotted as a function of mass for firebrands produced from the firebrand generator.

firebrands on the same level of magnitude as a single, burning 5.2 m (total height) Douglas-Fir tree [13]. For this size tree of low moisture content (18%), nominally 50 g of firebrands are produced [13]. It must be noted that this result was obtained for single-tree burns and did not include additional parameters, such as wind and the effects of adjacent trees. The device may simply be scaled up if larger mass loadings are necessary for ignition studies. The advantage of the firebrand generator is that the amount of firebrands produced depends upon the initial input

[1]Certain commercial equipments are identified to accurately describe the methods used; this in no way implies endorsement from NIST.

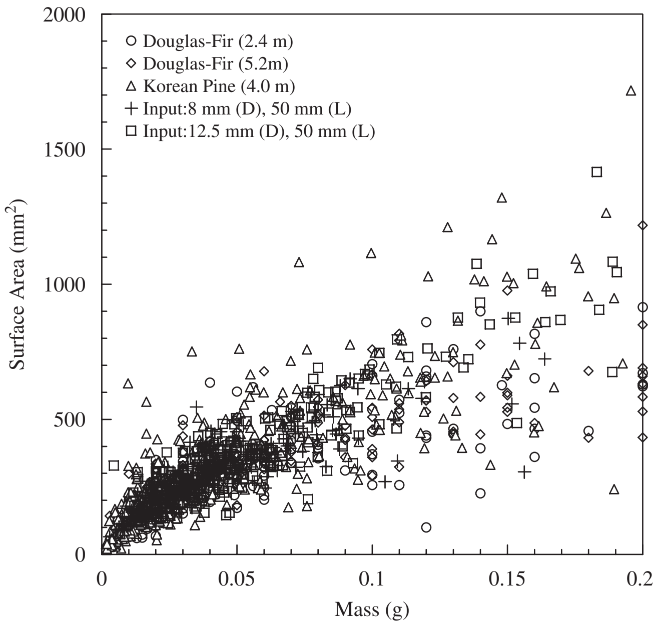

Fig. 9. Detailed comparison of firebrands produced from firebrand generator to those produced from burning trees.

conditions. Therefore, one can ‘engineer’ a distribution of interest by altering the input conditions.

4. Summary

A unique firebrand generator has been constructed in order to generate a controlled and repeatable size and mass distribution of glowing firebrands. The firebrand generator was fed with three different initial firebrand geometries; two different sized cylinders and one size of disks. Under baseline (no wind) conditions, the peak of the firebrand distribution occurred at pan locations 80–130 cm from the exit of the generator, independent of initial geometry used. After the baseline (no wind) distributions were determined, the wind speed was varied to investigate the lofting capability of the firebrands produced. The lofting distance increased as the wind speed was increased. At 9 m/s, each of the geometries tested resulted in the largest percentage of the number of firebrands lofted in the range of 580–630 cm (horizontal distance) from the generator.

The firebrand generator accurately represented the range of firebrands produced up to the mass class of 0.2 g. Beyond this, differences were observed between those firebrands produced by the apparatus to those produced by the burning of trees; the apparatus did not produce firebrands larger than 0.2 g. The result was due to the range of input conditions. The advantage of the firebrand generator is that the amount of firebrands produced depends upon the initial input conditions. Therefore, one can ‘engineer’ a distribution of interest. It is desired to use this device to determine ignition regime maps for real scale structures. Finally, the detailed findings regarding firebrand lofting may be used to validate a mode of firebrand transport.

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References

[1] V. Babrauskas, Ignition Handbook, Society of Fire Protection Engineers, Fire Science Publishers, Issaquah, WA, 2003 (Chapters 11, 14).
[2] Technology Assessment: Protecting Structures and Improving Communications During Wildland Fires, Government Accountability Office, GAO-05-380, April 2005.
[3] F. Albini, Spot fire distances from burning trees—a predictive model, USDA Forest Service General Technical Report INT-56, Missoula, MT, 1979.
[4] F. Albini, Transport of firebrands by line thermals, Combust. Sci. Technol. 32 (1983) 277–288.
[5] A. Muraszew, J.F. Fedele, Statistical model for spot fire spread, The Aerospace Corporation Report No. ATR-77758801, Los Angeles, CA, 1976.
[6] C.S. Tarifa, P.P. del Notario, F.G. Moreno, On the flight paths and lifetimes of burning particles of wood, Proc. Combust. Inst. 10 (1965) 1021–1037.
[7] C.S. Tarifa, P.P. del Notario, F.G. Moreno, Transport and combustion of fire brands, Instituto Nacional de Tecnica Aerospacial ‘‘Esteban Terradas,’’ Final Report of Grants FG-SP 114 and FG-SP-146, vol. 2, Madrid, Spain, 1967.
[8] S.D. Tse, A.C. Fernandez-Pello, On the flight paths of metal particles and embers generated by power lines in high winds and their potential to initiate wildfires, Fire Saf. J. 30 (1998) 333–356.
[9] J.P. Woycheese, Brand lofting and propagation for large-scale fires. Ph.D. Thesis, University of California, Berkeley, 2000.
[10] J.P. Woycheese, Wooden disk combustion for spot fire spread, in: S. Grayson (Ed.), Ninth Fire Science and Engineering Conference Proceedings (INTERFLAM) Interscience Communications, London, 2001, pp. 101–112.
[11] I.K. Knight, The design and construction of a vertical wind tunnel for the study of untethered firebrands in flight, Fire Technol. 37 (2001) 87–100.
[12] T.E. Waterman, Experimental Study of Firebrand Generation, IIT Research Institute, Project J6130, Chicago, IL, 1969.
[13] S.L. Manzello, A. Maranghides, W.E. Mell, Firebrand generation from burning vegetation, Int. J. Wildland Fire 16 (2007) 458–462.
[14] S.L. Manzello, J.R. Shields, A. Maranghides, W.E. Mell, Y. Hayashi, D. Nii, On the size and mass distribution of firebrands produced from burning Korean Pine trees, Fire Mater., 2007, in review.
[15] T.E. Waterman, A.N. Takata, Laboratory Study of Ignition of Host Materials by Firebrands, Project J6142–OCD Work Unit 2539A, IIT Research Institute, Chicago, IL, 1969.

[16] V.P. Dowling, Ignition of timber bridges in bushfires, Fire Saf. J. 22 (1994) 145–168.
[17] P.F. Ellis, The aerodynamic and combustion characteristics of eucalypt bark—a firebrand study, Ph.D. Dissertation, Australian National University, Canberra, 2000.
[18] S.L. Manzello, T.G. Cleary, J.R. Shields, J.C. Yang, On the ignition of fuel beds by firebrands, Fire Mater. 30 (2006) 77–87.
[19] S.L. Manzello, T.G. Cleary, J.R. Shields, J.C. Yang, Ignition of mulch and grasses by firebrands in wildland–urban interface (WUI) fires, Int. J. Wildland Fire 15 (2006) 427–431.