Flame Spread Along Fences Near a Structure in a Wind Field

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ABSTRACT

Combustible fences have been identified in post-fire investigations of wildland-urban interface (WUI) fires as potential threats to homes and other structures. They may ignite due to direct fire contact or firebrands, they may conduct fire along their length, and they may become sources of firebrands themselves. A new experimental protocol for studying the fire threat to structures posed by nearby fences has been developed. Flame spread rates and firebrand ignition characteristics were obtained for a fence positioned in front of a structure in a wind field. A western redcedar fence assembly was placed perpendicular to the wall of a small structure, separated from the structure by distances of 0 m, 0.30 m, 0.91 m, or 1.83 m. A wind field of 11 m/s aligned along the fence was generated by a large fan modulated by a flow straightener. The rate of flame spread for the fire moving continuously along the base of the fence was found to be a strong function of separation distance, with spread rates nearly an order of magnitude faster for 1.83 m separation distance than for either 0 m or 0.30 m. For each separation distance, a time delay was observed before firebrands began to ignite spot fires in the mulch bed next to the structure. After the first spot fire was observed, several others followed quickly. In every case except one, spot fires carried the fire to the structure wall within 7 min. In the exceptional case, little spotting was observed, and the fire took over 20 min to reach the wall.

1 INTRODUCTION

Post-fire investigations of wildland-urban interface (WUI) fires have identified combustible fences as a potential pathway by which fire can be spread to adjoining and nearby structures. The behavior of fences in fire is strongly affected by their linear nature; flames and ember generation may spread along their length, and the accumulation of combustible debris at their base may affect how easily they ignite. During the Waldo Canyon fire in 2012 in Colorado, ignited fences were observed on several streets transporting the fire directly toward adjacent structures and potentially serving as a source of firebrands threatening structures downwind [1]. An investigation of the Tanglewood Complex Fire near Amarillo, Texas in 2011 found that fences and railroad ties were defended multiple times over the course of the fire, demonstrating the potential of such landscaping features to generate flames and embers over an extended period of time [2].

A small number of studies have looked into some aspects of the behavior of fences in WUI fires. An Australian study [3] measured lateral flame spread along various fencing systems under a range of ambient outdoor conditions. Ignition of leaf litter distributed along the base and rails of the fencing was used as a proxy for firebrand attacks. Treated pine fences were much more likely to ignite and support lateral flame spread than hardwood fences.

In experiments carried out at the Building Research Institute in Japan, western redcedar and redwood fencing assemblies were found to be vulnerable to wind-driven firebrand showers [4]. With mulch beds below the fencing assemblies, flaming ignition in the mulch led to flaming ignition of the wood fence in every experiment. Without the mulch, firebrands resulted in smoldering ignition of the fencing assemblies which led to flaming ignition under the applied wind field.

Outdoor experiments conducted by NIST studied the spread of fire along a variety of wood privacy fence sections at various angles to a wind field generated by an airboat propeller [5]. Mulch was placed below most fence sections to simulate fine fuels often present in real conditions. Firebrands generated during the experiments were collected in water pans downwind, and pans of mulch tested the capability of these firebrands to cause ignition. The horizontal spread of fire along the fences was found to be fastest for moderately high winds (≈13.5 m/s) in a direction aligned with the fence. Smoldering ignition occurred in mulch targets as far downwind as 18 m.

In order to study the fire threat to structures posed by nearby fences, a series of experiments was planned to extend the previous series by placing the fence in close proximity to a small structure. A variety of fences, mulch types, wind speeds, and separation distances between fence and structure were investigated. The experiments were carried out at the Frederick County Fire & Rescue Training Facility in Maryland, U.S.A. As an example of the data that can be collected from this protocol, this paper presents the flame spread rates and firebrand spotting characteristics for a single wind speed, fence, and mulch type.

2 EXPERIMENTS

2.1 Experimental Setup

The configuration used for the set of experiments is shown in Fig. 1. A freestanding fence segment was assembled from a single western redcedar privacy fence panel 1.83 m tall by 2.44 m long, which was attached to 4x4 posts that were mounted on steel stands. Including the posts, the total length of each fence assembly was 2.62 m. The fence assembly was placed in a steel pan 0.91 m wide and 3.4 m long, with 0.04 m high sides. The pan was packed with 0.05 m of shredded hardwood mulch to represent fine combustible material such as ground cover or accumulated debris at the base of the fence. The bottom edge of the fence panel is adjusted so that it rests on the upper surface of the mulch.

The fence was positioned perpendicular to a small structure, 2.44 m on a side, whose wall facing the fence was covered by a non-combustible surface. At the bottom of this wall was a steel pan extending along its full 2.44 m length with a width of 0.46 m. The mulch packed 0.05 m deep within this pan was a surrogate for any structure vulnerability that enables ignitions from the direct spread of flames or the accumulation of firebrands. The endpoint for each experiment was the time at which flames reached the location of the wall.

Wind was generated by a large fan (an airboat propeller) 2.1 m in diameter at a distance of 10.7 m from the wall of the structure. A flow straightener tilted at 7° directed the airflow toward the ground in front of the fence and mulch pan. A bidirectional probe array holding 13 pressure probes measured the velocity component parallel to the ground for winds directed toward the fence.

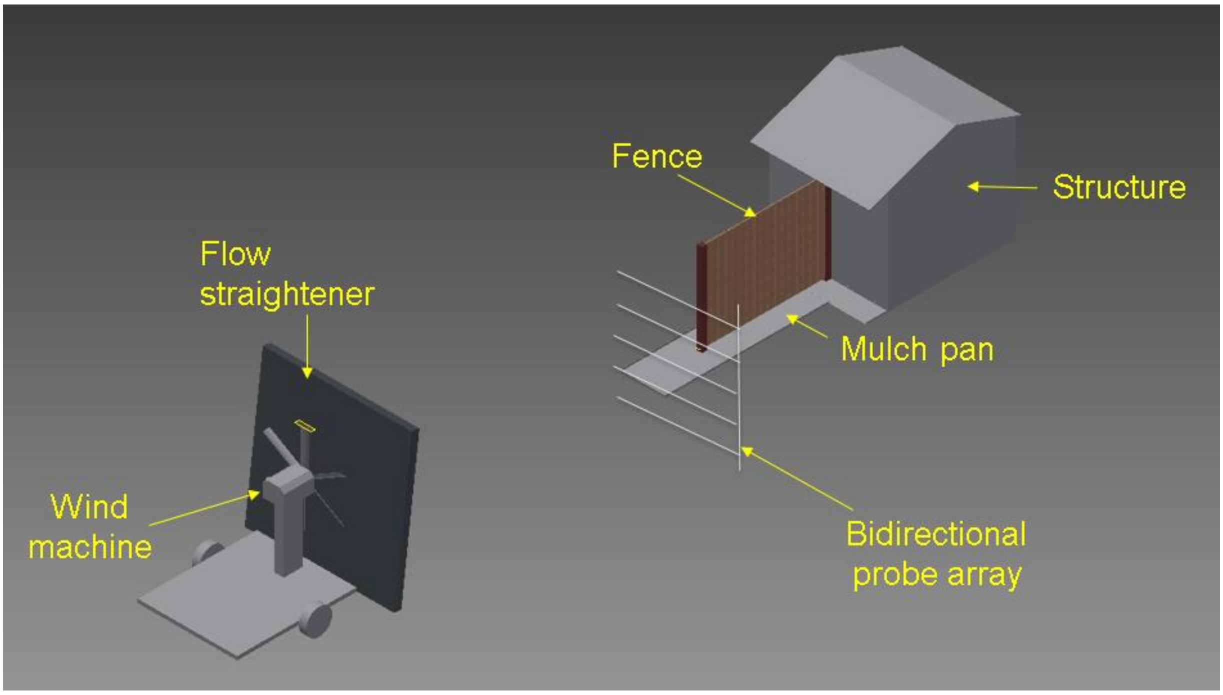

Fig. 1. Experimental setup.

Figure 2 shows the bidirectional probe from a vantage point in front of the fan. The probe array was positioned 1.22 m in front of the fence. Five probes were arranged at the tip of each rod in a vertical line along the centerline of the fence. The center rod, at 1.22 m from the ground, held 5 probes arranged horizontally, including the probe at the tip. The remaining 4 probes were distributed along the top and bottom rods.

Fig. 2. Experimental setup from point between fan and fence, showing position of bidirectional probe array.

Figure 3 shows the average wind velocity profiles along the vertical and horizontal lines of probes for four experiments run at the same fan setting but on different test days. The wind is time-averaged over the entire period of the experiment. These plots show that the wind speed from the fan is repeatable. Although the wind speed drops off at the highest probe, the velocities from the bottom of the fence at 0.05 m to the top of the fence at 1.88 m are reasonably uniform at 11 m/s ± 2 m/s.

Assuming that the horizontal profile in Fig. 3b is symmetric, the wind speed is observed to be uniform over the 0.91 m width of the mulch bed under the fence.

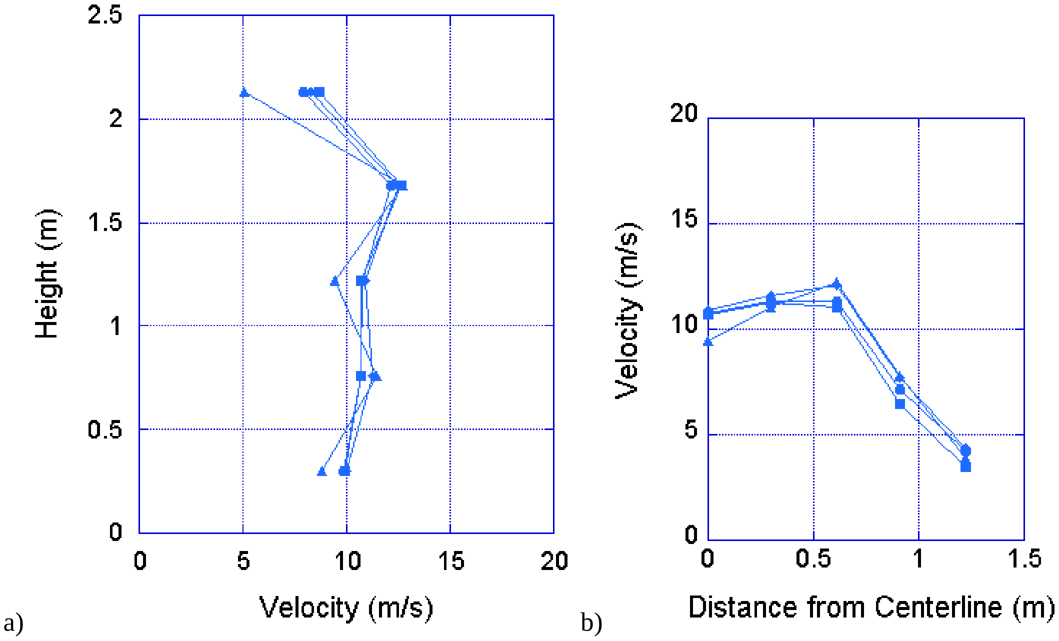

Fig. 3. Average velocity profiles from bidirectional probe array: a) along vertical line directly in front of fence and (b) along horizontal line at 1.22 m height above ground.

Experiments at this wind speed were carried out only when ambient winds were 3 m/s or less in order to minimize asymmetry between experimental conditions on left and right sides of the fence,

Experiments were run at four separation distances between the fence and the structure: 0 m, 0.30 m, 0.91 m, and 1.83 m. The configurations are shown in Fig. 4. This illustrates that, because of the mulch pan along the structure, only Cases 3 and 4 (0.91 m and 1.83 m separation distances respectively) have an actual space between the mulch under the fence and the mulch along the wall. Cases 3 and 4 are thus the only cases in this set of experiments that require firebrand spotting for the fire to reach the structure.

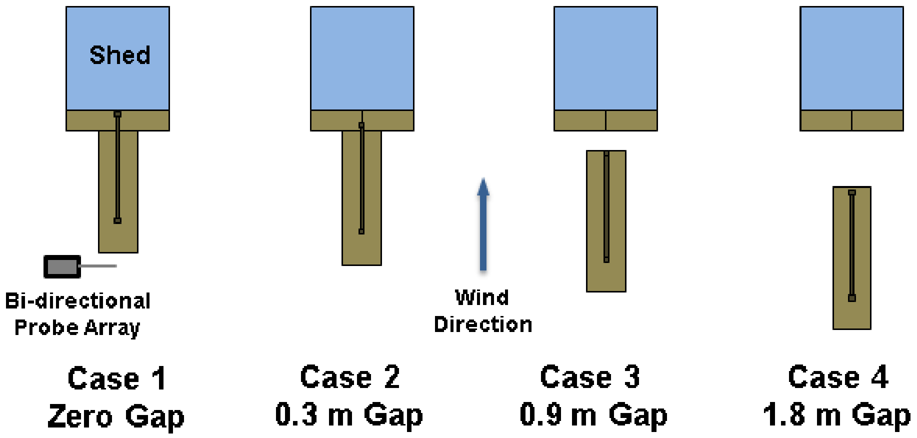

Fig. 4. Top view of combustible zone layouts.

Video records from each experiment were collected from four cameras. Two cameras were positioned on the right and left sides of the fence, with a view that encompassed the full length of the fence plus the mulch bed by the structure, and two cameras were placed to the right and left of the flow straightener in order to obtain an end view of the experiment. A digital clock placed to the right and just behind the forward wall of the structure served as the official timekeeper.

2.2 Experimental Procedure

Fences and hardwood mulch were obtained from local commercial suppliers. All materials were conditioned before use. Fences were stored in a conditioning shed that was held at 35 % relative humidity (RH). Mulch was dried either on pallets exposed to the sun or in aerated barrels with a steady airflow until the moisture content was under 7 % as measured in several locations by a moisture analyzer.

Before each experiment, the ambient wind conditions were checked to ensure that they were within the limits for the wind speed to be used. At the beginning of each experiment, the fence and mulch were ignited by a propane burner at the end of the fence closest to the fan. After the fire was well-established (typically at about 90 s after ignition), the wind machine was turned on, and the burner was removed. The fire was observed and recorded until flames reached the wall of the structure, either through steady progress of the flame ignited by the gas burner or by firebrand spot ignitions that spread to the wall.

3 ANALYSIS

3.1 Analysis Method

Determination of the position of the flame front and presence and location of firebrand spotting as a function of time required analysis of the video recorded during an experiment. To take these measurements, video frames were grabbed at appropriate time intervals from one or both of the cameras positioned to view the fence along its right or left side. MATLAB* was then used to view one of the images and generate a set of lines that captured the perspective view of the camera and defined locations on top of the mulch bed along the entire length of the fence.

An example is shown in Figs. 5 through 7. Starting with Fig. 5, the procedure involves determining the pixel locations in x and y directions for two points along the wall and two points along the edge of the mulch pan farthest from the wall. This defined the angles of perspective lines that encompassed the fence. Although distances were marked on the asphalt in later experiments, early experiments required scaling obtained from features in the videos. The two points where the outer edge of each fence post touches the top of the mulch bed determine the distance scale. A MATLAB routine was written to linearly interpolate a set of lines between the wall and the outer edge of the mulch pan, appropriately scaled for taking distance measurements. Figure 6 shows the resulting set of perspective lines for this experiment superimposed over the image. From this, the location of the flame front, defined as the furthest point of the charred (darkened) mulch continuous with the point of ignition, can be measured and recorded.

Fig. 5. Sample video image

* Certain commercial products are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the products identified are necessarily the best available for the purpose.

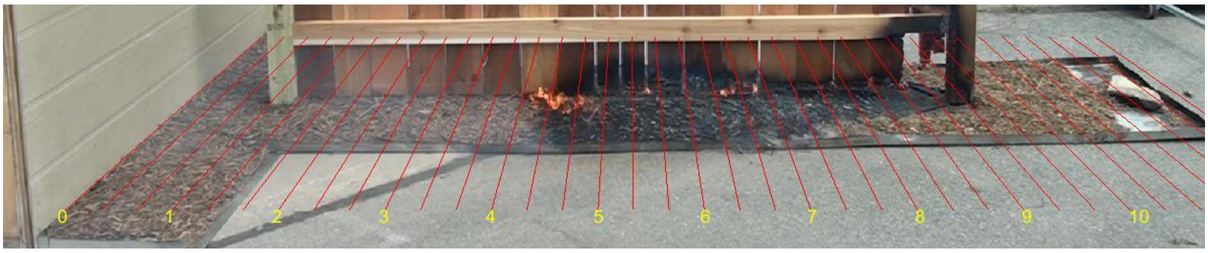

Fig. 6. Perspective lines superimposed on image

Because of shadows and other differences in lighting between each experiment and even between the right and left cameras during a single experiment, in addition to smoke, flames, and the inherent inhomogeneity of the mulch, the determination of the flame front location was not amenable to automation.

Figure 7 shows this same experiment at a later time, when the flame front is much closer to the wall. This image also shows a firebrand spot fire, whose position in the direction along the fence can be recorded in the same way. For firebrand spot fires, two locations were tracked – the flame fronts closest to and farthest from the wall.

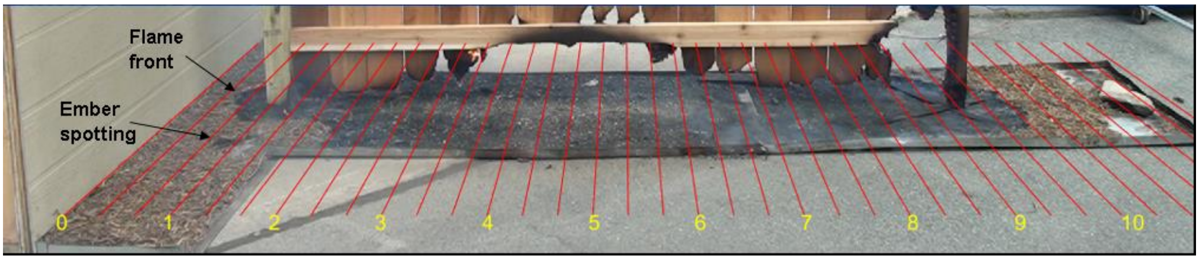

Fig. 7. Perspective lines superimposed on image near the end of the experiment, showing the location of the main flame front and firebrand spotting.

One of the issues with these experiments was the question of how to establish an initial time. Many factors influence the establishment of ignition and initial flame spread in this experiment, including the variability of fuels, the details of gas burner placement, and the ambient environment, including the changes in wind while the large fan is being adjusted to the desired speed. A transient period of slower flame spread has been observed in many of the experiments. In order to bypass the period during which transient effects are dominant, we chose to define time t = 0 s as the time at which the flame front passes a specific point. The point along the fence 2 m from the end nearest the wall was chosen as a starting location that eliminates the transient effects without losing much of the data.

There are several potential sources of error in this data acquisition. First, the locations of the six points on the image used for the MATLAB calculation can be off by perhaps as much as 1 cm due to uneven piling of mulch against the wall and the distortions in the mulch pan. The camera may have some distortions in the lens system that throw off the assumption of linearity used to create the set of perspective lines. The camera may vibrate in the wind, causing the image to move under the superimposed lines. Finally, estimating the location of the flame front may be challenging, depending on the contrast between burned and unburned areas caused by the lighting and the presence of flames in the image, as well as by the ambiguity in the exact location of the flame front in the shredded hardwood mulch, which is typically not a straight line. The latter source of uncertainty is expected to dominate the others. It is estimated to be on the order of ±3 cm.

3.2 Flame Spread Rate

A set of five experiments for western redcedar privacy fences with shredded hardwood mulch filling the mulch pans beneath the fence and along the structure wall enables an estimate of the flame spread rate as a function of separation distance between the fence and the structure. The experiments include one each at 0 m, 0.91 m, and 1.83 m separation and two experiments at 0.30 m separation. The video from cameras facing the left side of the fences has been analyzed for all experiments, and the video from the right-side camera has been analyzed for two experiments Although replication of the experiments is needed to build confidence in the numerical results, these experiments can provide some preliminary insights.

The location of the flame front as a function of time for each of these seven cases is shown in Fig. 8. Time t=0 is defined as the time at which the flame front has reached the point at separation distance plus 2 m. As can be observed from the plot, the initial flame spread rate, or the magnitude of the slope of flame front location vs. time, appears to be steady in each of these cases. The initial flame spread rates are very close for the replicated case at 0.30 m separation distance and for the two cases where videos from both right and left cameras have been analyzed.

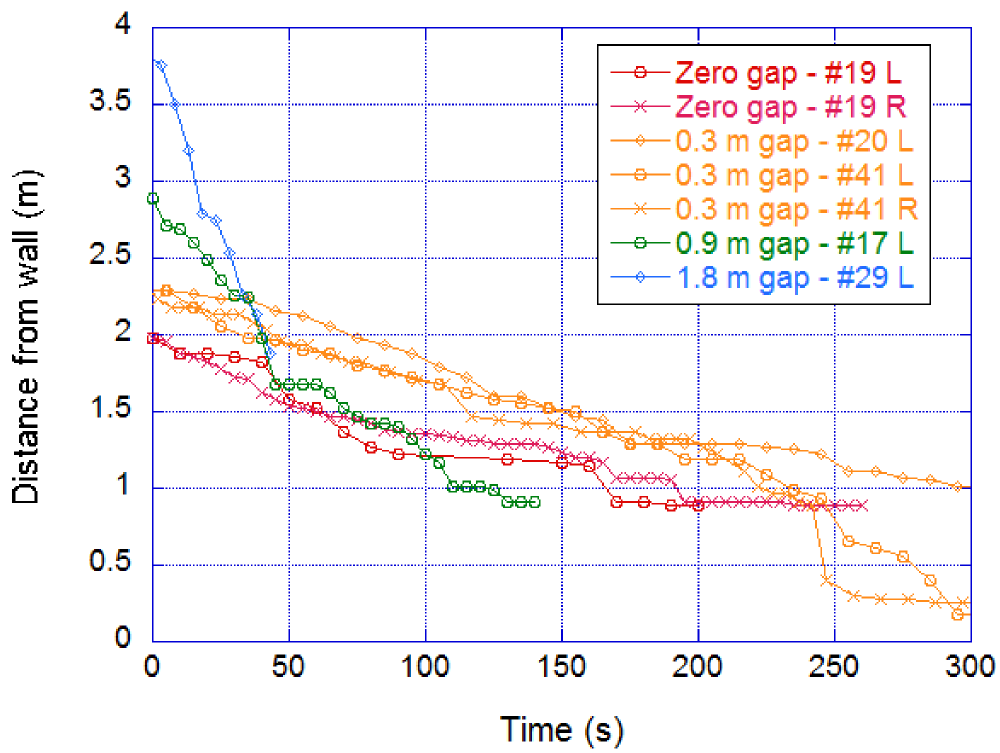

Fig. 8. Location of flame front as a function of time and separation distance between fence and structure.

Calculating the flame spread rates at each of the four separation distances results in the plot in Fig. 9. The flame spread rate is the same for 0 m and 0.30 m separation distances between fence and wall and increases strongly for distances of 0.91 m and 1.83 m.

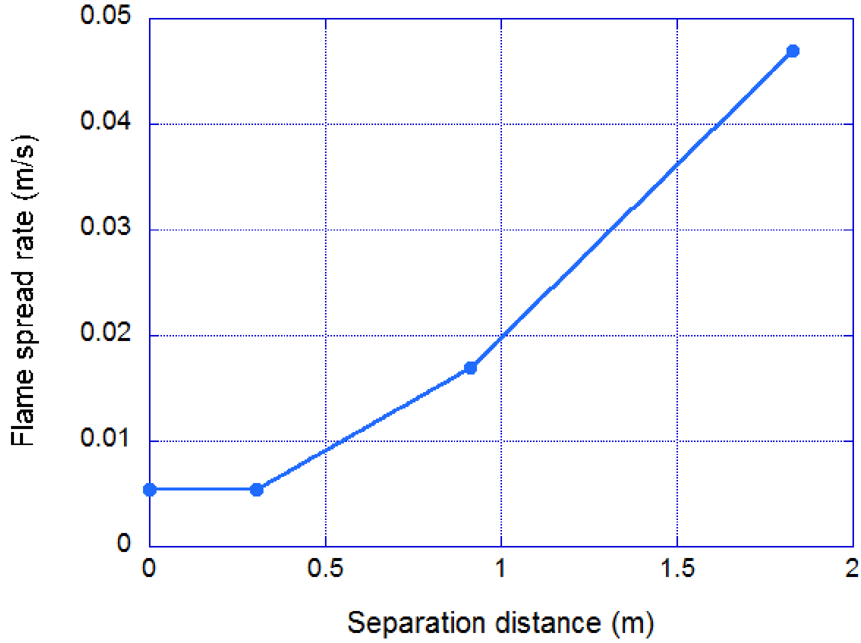

Fig. 9. Flame spread rate along fence as a function of separation distance between fence and structure.

A possible explanation for this strong dependence of flame spread rate on separation distance is suggested in Fig. 10. The Fire Dynamics Simulator (FDS) software [6] was used to develop a coarse model of the experimental setup in order to observe the general flow characteristics from a fan directed toward a structure. No fence is included in this model. The identical flow patterns in Figs. 10 a and b show a vortex near the ground in front of the structure, consistent with experimental and numerical studies of flow around a surface-mounted cubic obstacle [7-9]. For a flame front near the ground that is approaching the structure from a distance, the winds are in the same direction as, or concurrent with, the flame spread. A flame front closer to the structure encounters opposing wind flow, and the flame spread is slower. The black rectangle in Fig. 10a represents the spatial extent of a fence assembly at 0 m separation from the structure. The flames approaching the structure in the mulch bed at the base of this fence spread slowly due to the opposing flow generated by the vortex. The fence in Fig. 10b, on the other hand, is almost entirely outside of the vortex. The flame spread in this concurrent flow would be expected to be faster throughout the entire burning period.

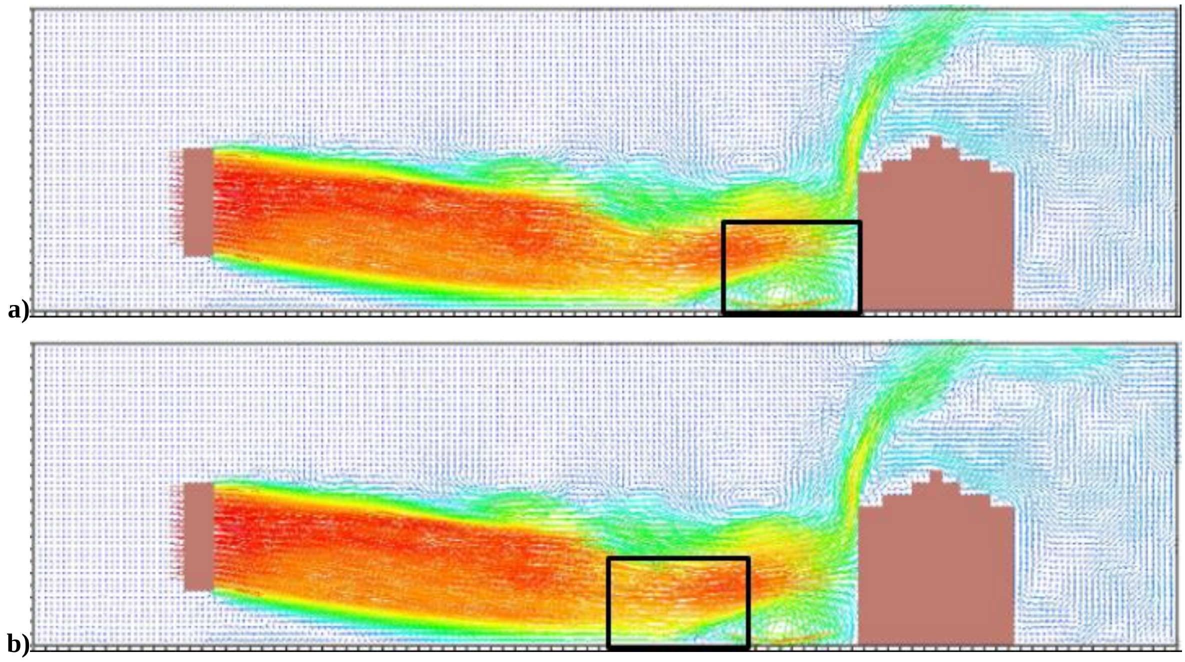

Fig. 10. FDS model showing vortex near structure, with fence dimensions superimposed at a) 0 m separation and b) 1.83 m separation. Instantaneous velocity vectors are colored by magnitude.

3.3 Firebrand Ignitions

The location of each spot fire ignited by firebrands as a function of time can be tracked in the same way as the location of the main flame front as it advances from the point of the gas burner ignition towards the wall. Each firebrand that ignites the mulch creates a spot fire that can grow in both directions – toward the wall and away from it – until it reaches and is absorbed by the main flame front.

Some insight into the quantity and timing of spot fires for each experiment can be obtained by switching the axes used in Fig. 8. In Fig. 11, the red line shows the same data for experiment #19 R that was plotted in Fig. 8, but here the y-axis is time and the x-axis is distance from the wall. The ignition point of each spot fire that occurred during this experiment is plotted as an asterisk, with two lines that track the spot fire fronts toward and away from the wall extending forward in time. Each spot fire widens with time. The value of this plot can be seen by looking at the dashed green horizontal line at t=120 s. By following this line from the point of contact with the wall on the left to the location of the flame front at about 1.7 m from the wall, we see that at time t=120 s there are four spot fires: two within the mulch bed along the shed wall (the region marked by the vertical line at 0.46 m from the wall) and two within the mulch bed along the fence. Looking horizontally along a given time provides a snapshot of the locations of mulch that have been burned or are burning at that time.

Figures 11 through 15 plot the extent of the burned region as a function of time for cases with fence separation from the structure from 0 m to 1.83 m. In each plot, the main flame front is indicated by a line with the same color used in Fig. 8. Everything to the right of this line can be considered to have burned or be burning. Each asterisk in these plots indicates the location of a firebrand at the initiation of a firebrand spot fire. Firebrand spot fires typically grew faster in the direction away from the structure than toward it – a phenomenon that is again consistent with the presence of a vortex near the structure that generates winds in the direction away from the structure at ground level.

The vertical lines at 0.46 m in each plot indicate the maximum extent of the mulch bed next to the structure. Firebrand spotting to the left of this line may occur anywhere along the base of the structure, whereas spotting to the right of the line is limited to the mulch bed under the fence. Spotting ahead of the main flame front occasionally results in a jump in the colored line, as the main flame front catches up to and incorporates the firebrand spot.

The second vertical line in Figs. 13 and 14 marks the end of the fence and associated mulch bed for these separation distances. There is no fuel between this location and the start of the mulch bed next to the structure, so the only way fire can spread to the wall in these cases is by way of firebrands.

Figures 11 through 14 show that in each of these cases firebrand spotting in the mulch bed near the structure begins between about 2 min and 3 min after time t=0. After this delay, continued spotting is seen.

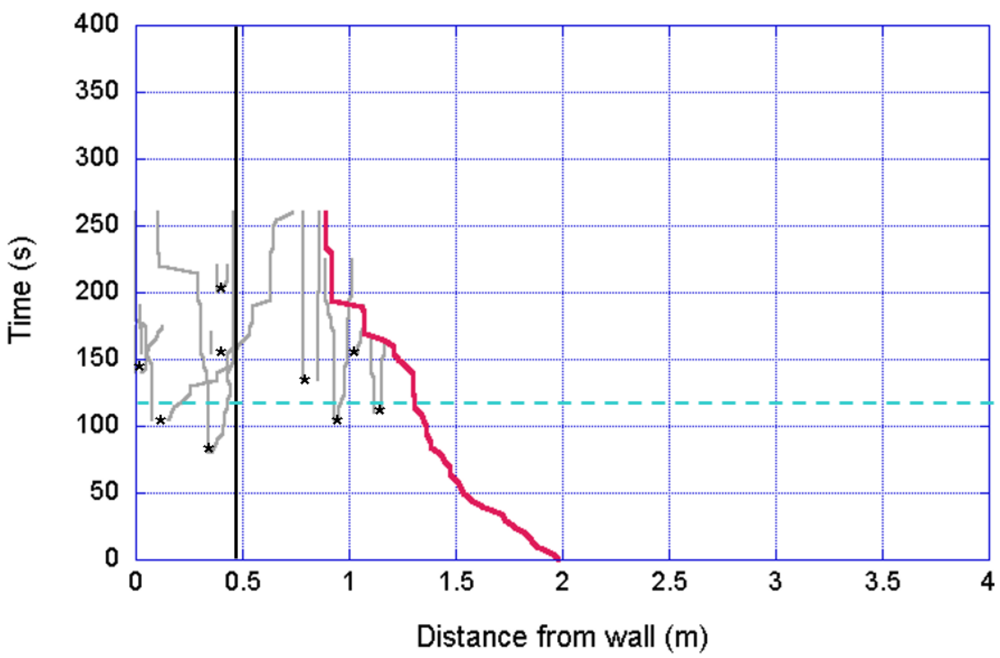

Fig. 11. Flame spread due to piloted and firebrand ignitions for 11 m/s winds and fence separation distance of 0 m (Experiment #19 R). Dashed green line is an example illustrating the distribution of burned mulch at a selected time.

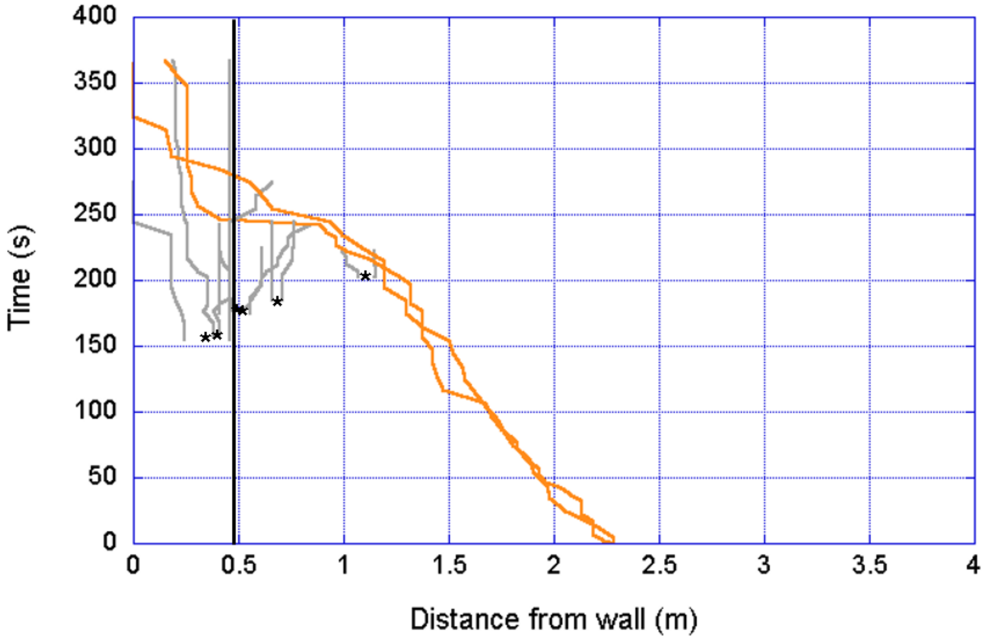

Fig. 12. Flame spread due to piloted and firebrand ignitions for 11 m/s winds and fence separation distance of 0.30 m (Experiment #41 L&R).

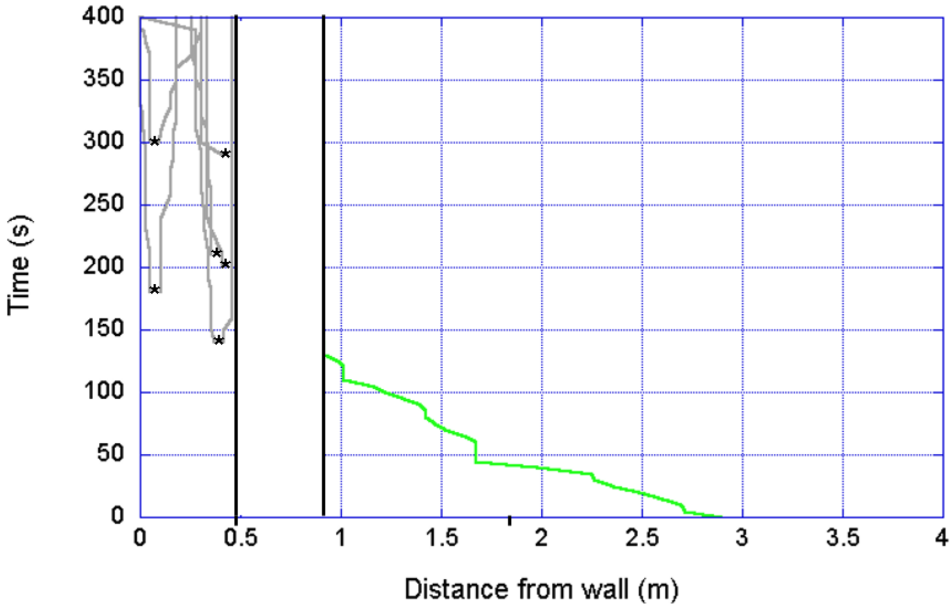

Fig. 13. Flame spread due to piloted and firebrand ignitions for 11 m/s winds and fence separation distance of 0.91 m (Experiment #17 L).

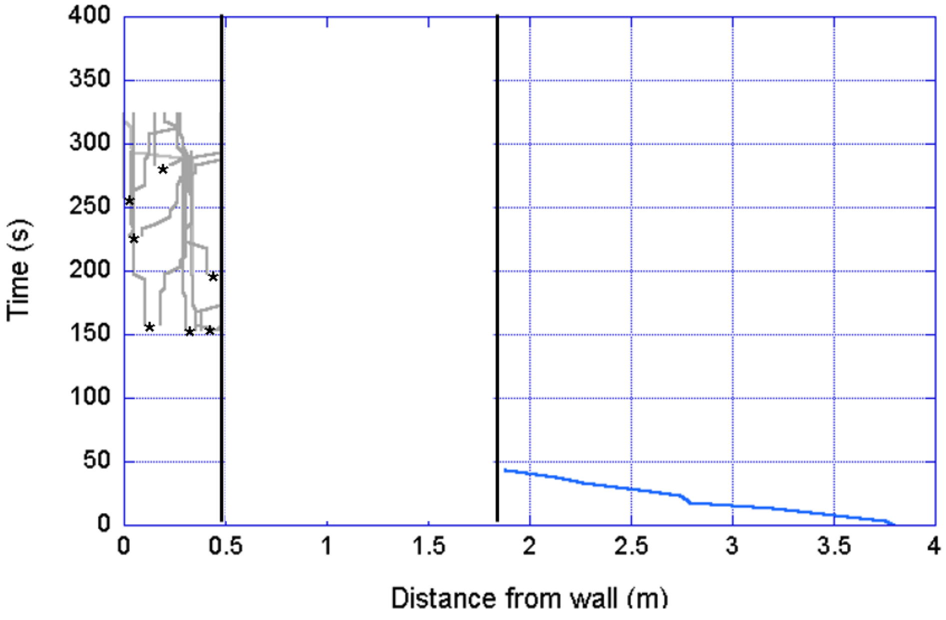

Fig. 14. Flame spread due to piloted and firebrand ignitions for 11 m/s winds and fence separation distance of 1.83 m (Experiment #29 L).

Figure 15 shows an unusual case in which little firebrand spotting occurred. The main flame front in this case continued to approach the structure for over 20 min, a much longer period than for the other experiments which were stopped after firebrand spotting reached the structure in 7 min or less. Note that the flame spread in this case slows gradually as it approaches the structure, consistent with going from a concurrent to an opposing wind condition due to the wind vortex. This experiment is included in Fig. 8, which shows that the initial flame spread rate is consistent with the other case (#41) at the same separation distance.

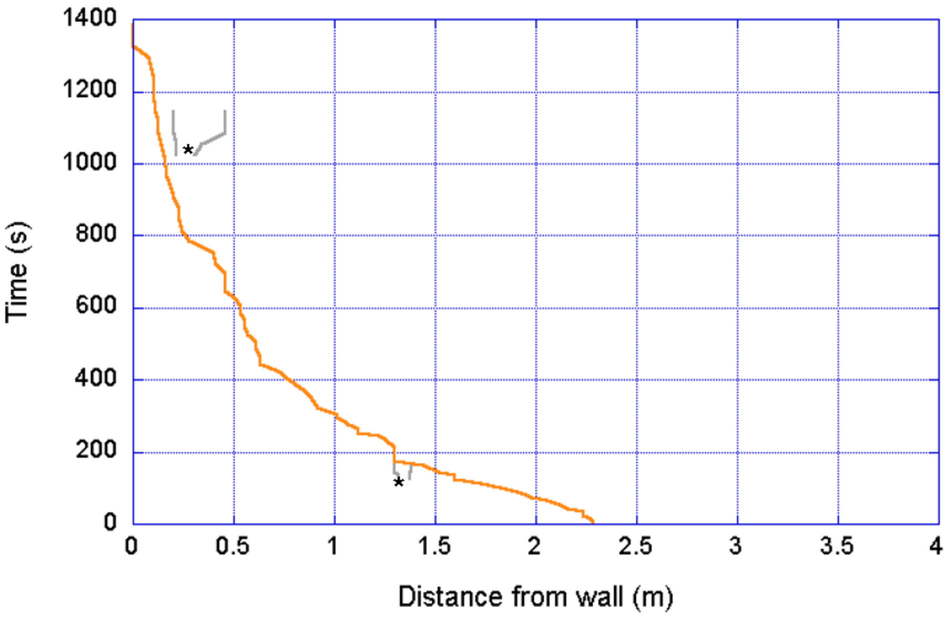

Fig. 15. Flame spread due to piloted and firebrand ignitions for 11 m/s winds and fence separation distance of 0.30 m (Experiment #20 L).

4 CONCLUSIONS

A new experimental protocol has been developed to provide the scientific basis for the investigation of flame spread and firebrand spotting for fencing assemblies near a structure under windy conditions similar to those encountered in WUI fires. An analysis procedure has been developed to obtain flame spread rate and the growth rate of regions ignited from firebrands from these experiments.

The flame spread rate and firebrand spotting characteristics have been explored for a series of experiments on western redcedar privacy fences in a shredded hardwood mulch bed in an 11 m/s wind at distances from 0 m to 1.83 m from a structure. The results show that the flame spread rate from a fire ignited by a gas burner near the far end of the fence is independent of separation distance for fences close to the structure (within 0.30 m) but increases rapidly for larger separation distances. In one case in which spotting was not prevalent, the flame spread slowed as the flame front approached the wall. It is suggested that both of these effects are related to the vortex that forms near the ground in front of a structure when wind is directed toward the structure.

For fence distances from the structure from 0 m to 1.8 m, firebrand spotting was observed in the mulch bed near the structure after a two- to three-minute delay. The firebrand spot fires grew more quickly in the direction away from the structure than toward it. This is again consistent with the vortex flow pattern near the structure.

Additional sets of experiments and analyses are underway to investigate the effects of different fence and mulch types, wind speeds, and orientations of the fan in relation to the fence-structure assembly. Any changes in the fire behavior of fences with aging are of particular interest, as are the possible mitigating effects of coatings or other treatments. The results of the full investigation will be used to guide future test method development for fencing assemblies. A similar set of experiments is also underway to study the impact of wood piles on nearby structures in WUI fires.

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