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Ignition propensity of structural materials exposed to multiple firebrands in wildland-urban interface (WUI) fires: effects of firebrand distribution and ambient wind

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Abstract: Firebrands are known to be able to ignite not only vegetation but also various structures found in wildland-urban interface (WUI) area. Especially, firebrands located close to each other on a combustible substrate increase the likelihood of ignition and the subsequent fire. To elucidate the ignition mechanism of firebrands, experiments are performed using a 3 by 3 square array of flaming firebrands deposited on a 6.35 mm thick birch plywood. The spacing of the firebrand is varied in each experiment, ranging from 10 to 30 mm. The deposited mass of firebrands lies between 13 and 15 g. Ambient wind is imposed parallel to the plywood surface to investigate its effect on the ignition and the subsequent flame spread over the fuel. Three different wind speeds 0, 0.5, and 0.75 m/s are tested. During the experiments, mass loss of the plywood and the deposited firebrands is recorded. Video cameras are used to monitor the burning process. An infrared camera is also used to monitor the temperature of the firebrands and the plywood. The experiment results indicate that the firebrands with the spacing greater than 20 mm are able to burn only the surface of the plywood until the firebrands burn out. When the spacing between firebrands is smaller than 20 mm, the plywood is ignited and continues to burn even after the firebrands are fully consumed. It is also observed that the flame is able to spread downstream at 10 mm spacing under ambient wind speed of 0.5 m/s. Results from this study demonstrate the significant influence of spacing between the firebrands on the ignition and the burning behavior of the substrate materials.

Keywords: *firebrand ignition, spacing between firebrands, wildland-urban-interface (WUI)*

1. Introduction

Wildfire has devastated more and more areas across the United States for the past several decades [1]. Especially, the west coast of the United States suffers from severe wildfires recurring every year [2]. Unfortunately, the severity of wildfires is expected to increase as the weather conditions worsens due to global warming [3]. Dry vegetation resulting from a drought can contribute to an extreme wildfire which burns a wider area, increases the suppression cost, and deteriorates the air quality by wildfire smoke [4,5]. With frequent wildfire activities, the wildland urban interface (WUI), a built environment located nearby a forest or intermingles with wildland vegetation, is under great threat [5]. In California, it was reported that the majority of the structure losses due to wildfire occurred in WUI areas [6]. Therefore, it is crucial to study the mechanism of wildfire spread within WUI to minimize the damage from the destructive wildfires such as 2017 Tubbs fire and 2018 Camp fire [2].

Recently, there have been efforts to quantify the critical conditions for firebrand-induced ignition. Some studies investigated the thermal characteristics of a pile of firebrands on an inert plate [7–9]. These experiments demonstrate that the heating from a firebrand pile is influenced by not only ambient wind speed but also by the deposited mass and bulk density of the firebrands. Hakes et al. found that the heating time increases with deposited pile mass although the peak heat flux converges to a certain value [7]. The diameter of firebrands was found to have little influence on heat generation from a firebrand pile. In the experiments by Tao et al., it was shown that the heat flux from a pile of natural fuels such as sticks and barks intensified with smaller bulk density of the firebrand pile [8]. However, the reverse trend was observed with a pile of artificially fabricated fuels. These illustrate the complexity in the mechanism of multiple firebrands and the role of environmental factors surrounding the firebrands. Therefore, more studies are required to elucidate the influence of firebrands in a close proximity on the ignition process.

The objective of this study is to investigate the ignition process of a building material commonly found in the wildland-urban interface area. We focused on the effects of spacing between multiple firebrands on their ignition capabilities. The air flow speed was also varied to consider the significant influence of wind on the combustion of wood material.

2. Experimental Setup

The experimental apparatus was designed to investigate the ignition process of a common building material by multiple firebrands as shown in Figure 1. The apparatus consists of the coil igniter, transporter, and the test section. The coil igniter was described in the author's paper [10]. The firebrands ignited by the coil igniter were transported and dropped on the test section by the transporter. The transporter was made of aluminum frames and stainless steel wires whose diameter is 0.36 mm (0.014") to support the burning firebrands in the air. Once the transporter reached the test section after the firebrands burned for a specified time, the triggers were activated to drop the firebrands on the fuel substrate with the intended spacing (s) between them.

The materials for firebrands and a fuel substrate were the untreated birch wooden cubes whose length is 19.05 mm (3/4") and a birch plywood of 203.2 mm by 203.2 mm (8" by 8") with 6.35 mm (1/4") in thickness. The birch wooden cubes were fully dried in an oven before each test to remove moisture content. The side and bottom surfaces of the plywood were surrounded by a ceramic fiber board for insulation purpose. Both plywood and the ceramic fiber board were positioned on top of the precision balance (A&D GX-8K) with 0.01 g accuracy to read the mass loss during the experiments. The grain direction of the plywood was vertical to the flow direction. The wind tunnel was constructed to create a specific speed of flow condition over the plywood. To allow the transporter to reach the plywood surface, the wind tunnel was separated by two tunnels. This made the test section of the plywood on the ceramic fiber board open to the air. The fore part of the tunnel has a cross section of 254 mm by 254 mm (10" by 10") and 609.6 mm (24") long with an aluminum honeycomb panel whose thickness of 25.4 mm (1") at the outlet. The flow speed was carefully controlled by four DC power fans. The flow speed for each experiment was measured at the center of the plywood using the anemometer (PCE-423). In the test measuring the flow speed at 25 points in square pattern with 25.4 mm (1") spacing, the discrepancy of the flow speed were ± 0.03 m/s and ± 0.04 m/s for the flow speed at 0.5 m/s and 0.75 m/s at the center of the plywood.

The temperature across the plywood was recorded by the infrared (IR) camera (FLIR, T560 with a lens of $f = 17$ mm, 24°) at 30 frames per second. The emissivity of wood char was set to 0.95 [11]. The temperature measurement range of the IR camera was selected from 0 °C to 650 °C. A

DSLR camera (Canon T3i) was installed next to the IR camera to acquire the visual images of the experiments (ISO: auto, shutter speed: 1/40, aperture: F1.8).

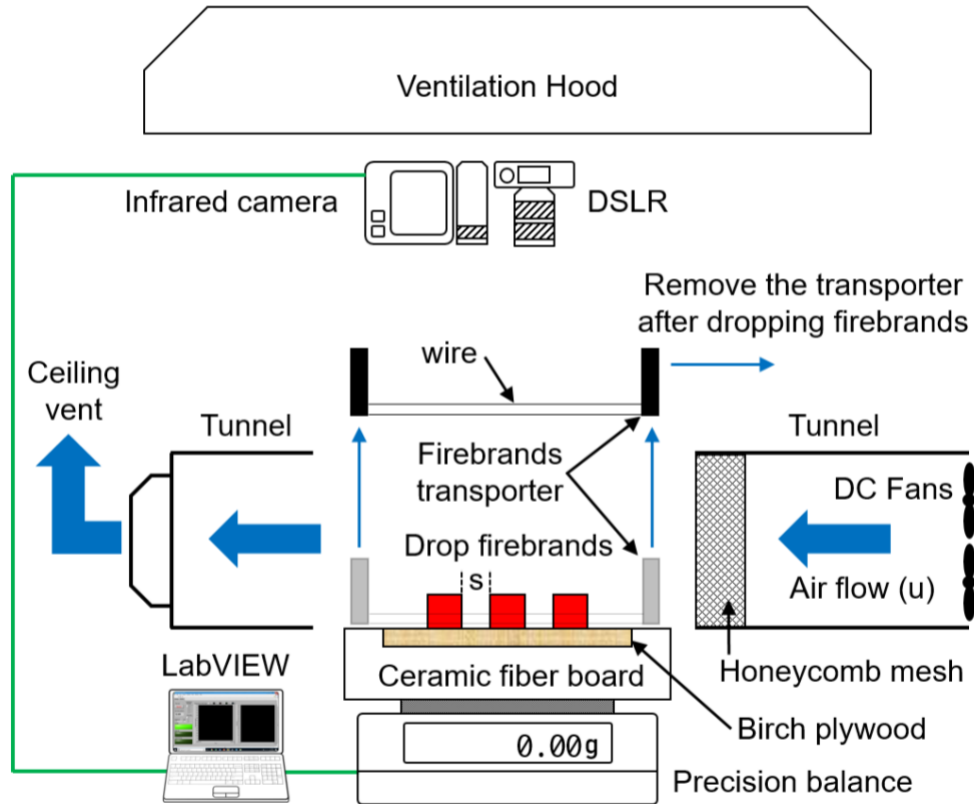


Figure 1. The experimental apparatus to simulate the firebrand induced ignition under a specific flow condition.

3. Results and Discussion

Table 1 shows the test matrix conducted in this study. The deposited mass is the mass reading of the precision balance when the firebrands were dropped. The spacing (s) between firebrands was varied from 10 to 30 mm for 9 firebrands. The flow speed (u) of 0, 0.5 and 0.75 m/s were taken into account to investigate the effects of flow speed. In all experiments, the firebrands were flaming when being dropped on the plywood. The room temperature was maintained between 21.1 °C and 26.7 °C. The humidity varied from 15 % to 25 %.

Table 1. The test matrix

Number of firebrands	Deposited mass (g)	s (mm)	u (m/s)
1	1.59 ± 0.19	-	0 / 0.5
9	13.60 ± 0.06	10	0 / 0.5 / 0.75
9	13.86 ± 0.83	20	0 / 0.5 / 0.75
9	16.57 ± 2.16	30	0 / 0.5 / 0.75



Figure 2. Sequential images of the experiments since the firebrands drop (defined as $t = 0$ s) under $u = 0.5$ m/s (a) $s = 10$ mm and (b) $s = 30$ mm. (wind direction is from bottom to up)

3.1 Ignition and sustained fire of a plywood at $s = 10$ and 30 mm

Figure 2 shows the overall ignition and burning process of a plywood during the experiments at $s = 10$ and 30 mm under $u = 0.5$ m/s. The experiment started when the firebrands were dropped on the plywood substrate ($t = 0$ s). At $s = 10$ mm, Figure 2(a), the center of the plywood was charred quickly by the flaming firebrands and eventually ignited. Due to the wind and close proximity, the fires on the firebrands were merged and became longer. The plywood burning was clearly visible when fires on the firebrands were extinguished at $t = 100$ s. At $t = 200$ s, fire on the plywood was weak blue flame and all fires on the firebrands were extinguished. Later, fire on the plywood started growing and became larger as the plywood layers were separated and new layer was exposed to the flame as seen at $t = 300$ and 400 s. After the fire was extinguished, the plywood continued smoldering as the temperature cooled down to the room temperature.

In the experiment at $s = 30$ mm in Figure 2(b), on the other hand, the plywood was ignited only nearby the firebrands. Though the plywood between the firebrands on the first and second row on the right side was ignited, fire was not sustained and extinguished soon. In the comparison of IR images at $t = 50$ s in Figure 3, a plywood between the firebrands is heated higher at $s = 10$ mm as seen in Figure 3(a) whereas the plywood between firebrands at $s = 30$ mm is less affected.

Temperature measurements along x and y directions denoted in Figure 3 are compared in Figure 4. It can be seen that x -direction (cross-stream) temperature distribution at $s = 10$ mm (Figure 3a) is higher than 200 °C right after the firebrands landed. This is because the plywood surface was heated by firebrands for $5 \sim 7$ seconds before the firebrands dropped according to the experimental procedure. As the experiment in progress, temperature also increases across all x coordinates. However, x -temperature between the firebrands at $s = 30$ mm remains under 130 °C (Figure 3c). Based on thermogravimetric analysis (TGA) in the previous study [10], it was found that birch

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wood pyrolysis under air reached the shoulder at $\sim 276.85^\circ\text{C}$ (550 K) and the peak value at $\sim 326.85^\circ\text{C}$ (600 K). This indicates that $s = 30\text{ mm}$ is too far for the firebrands to raise the substrate temperature and cause a sustained fire on a plywood. In the wind flow direction, y-direction, temperature is hotter than x direction. This is because the wind caused the flame to tilt downstream at both spacing (Figure 3b and 3d).

Figure 5 shows the evolution of maximum temperature (red line) and the evolution of area where temperature exceeds 276.85°C (black line). The maximum temperature is found to be higher and maintains for a longer duration at $s = 10\text{ mm}$ due to close spacing. From the area comparison (black line), the firebrands located in proximity can heat a wider area with a longer duration compared to $s = 30\text{ mm}$. The charring area is also compared (blue line in Figure 5). The pyrolyzed area is defined if the solid surface temperature exceeds 276.85°C at any moment. At $s = 10\text{ mm}$, the pyrolyzed area continues increasing until $t \sim 600\text{ s}$, indicating that fire grows across a wider area. On the other hand, the pyrolyzed area at $s = 30\text{ mm}$ increases only for the first 50 s.

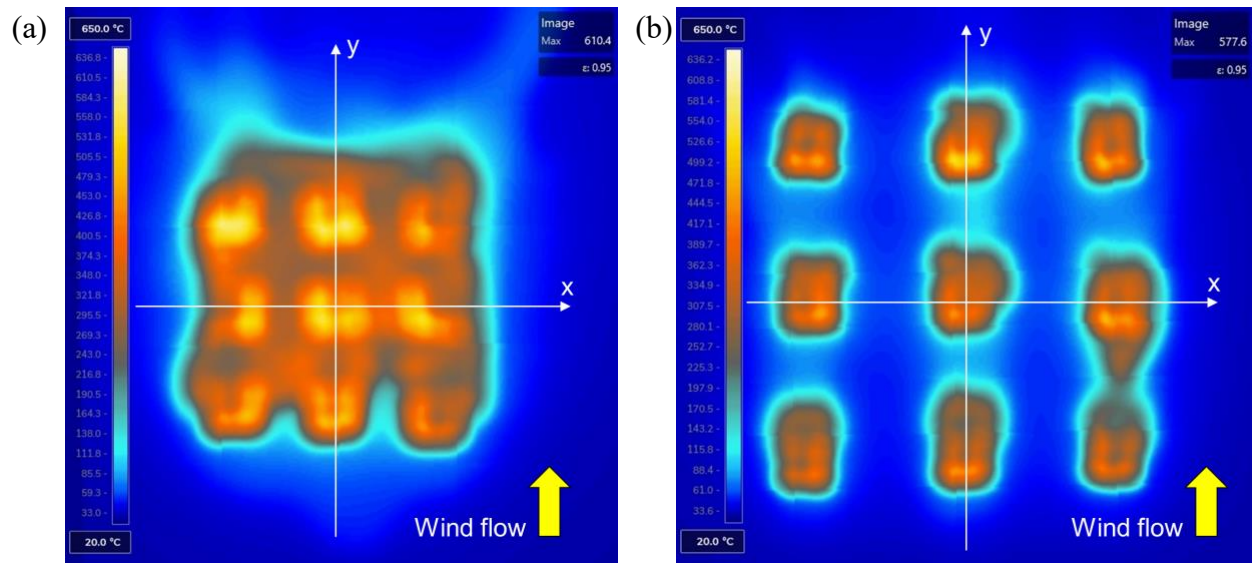


Figure 3. Infrared images at 50 seconds (a) $s = 10\text{ mm}$ and (b) $s = 30\text{ mm}$. Wind direction is bottom to top (positive y-direction).

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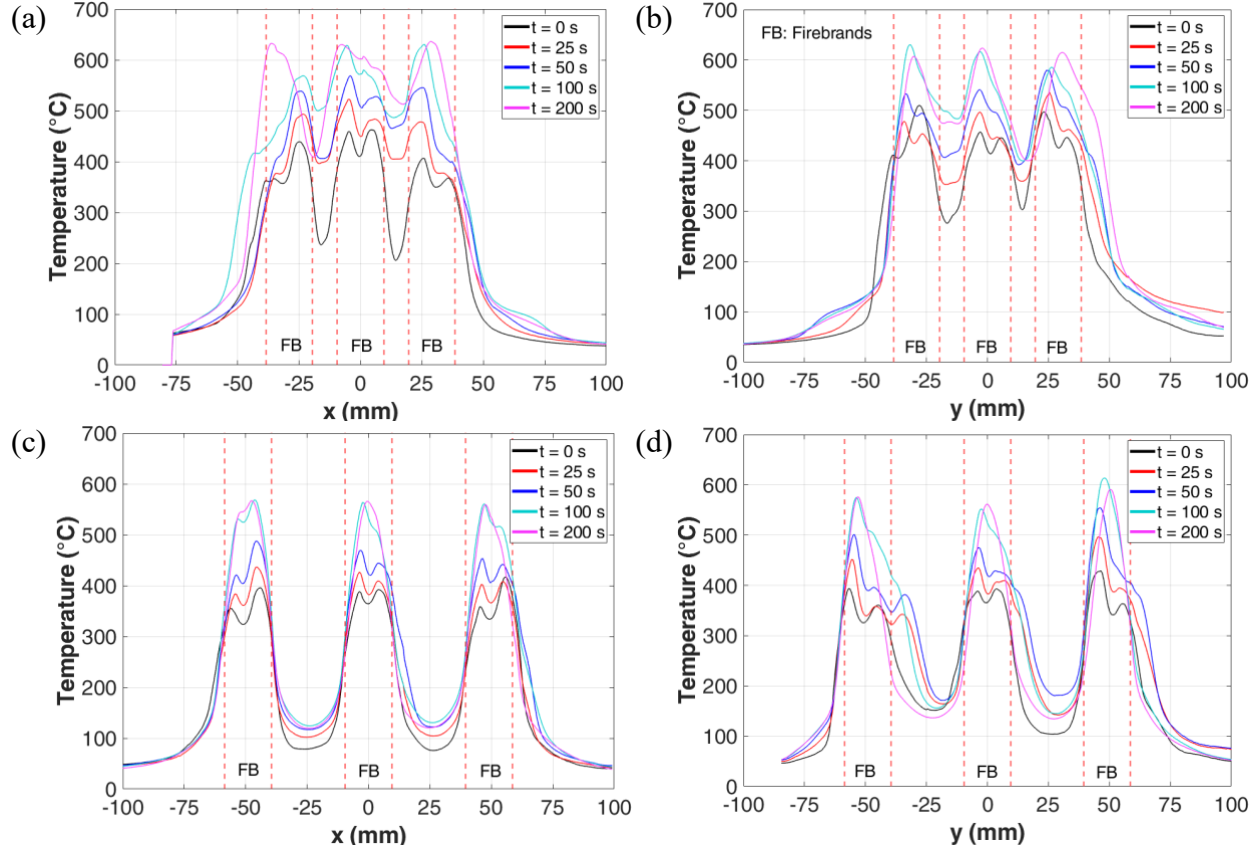


Figure 4. Temperature measurements along x and y directions in Figure 3. (a) $s = 10$ mm, cross-stream (x-) direction, (b) $s = 10$ mm, stream (y-) direction, (c) $s = 30$ mm, cross-stream (x-) direction, and (d) $s = 30$ mm, stream (y-) direction.

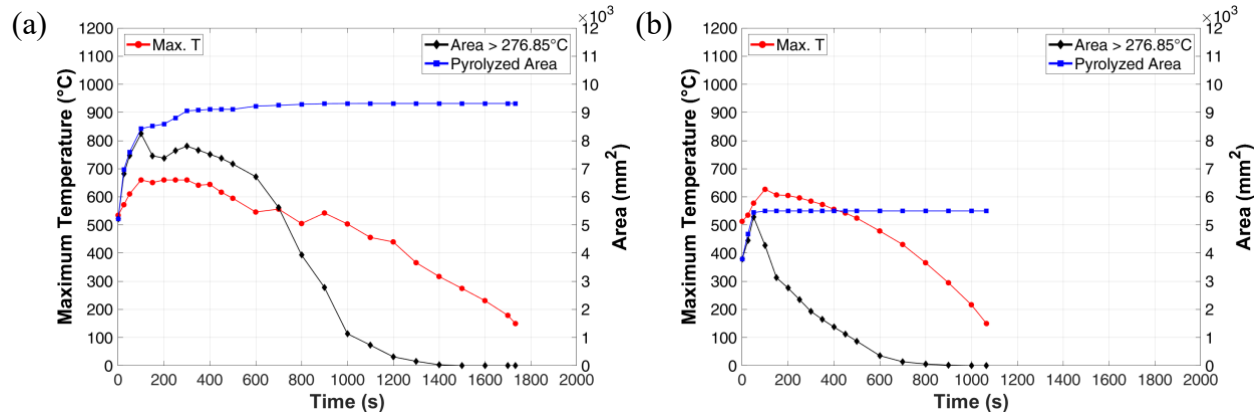


Figure 5. The maximum temperature and the area where the temperature exceeds 276.85 °C. (a) $s = 10$ mm, (b) $s = 30$ mm

3.2 The effects of spacing and flow speed

The observed fire events are summarized in Figure 6. At $s = 10$ and 20 mm, for all tested ambient wind speeds, the plywood substrate was ignited, and fire grew even after the firebrands extinguished. At $s = 30$ mm and in the case of one single firebrand, no sustained fire was observed regardless of the ambient wind speed.

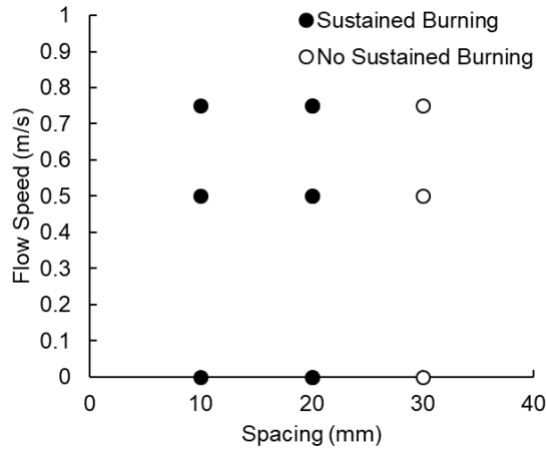


Figure 6. The sustained fire occurrence depending on flow speed and spacing

The mass and mass loss rate at $s = 10$, 20 and 30 mm are plotted in Figure 7. In all cases, the mass loss rate was high initially after the firebrands landed. The mass loss rate decreased as the firebrands were consumed. After that, in the case of $s = 10$ mm, mass loss rate increased again when fire grew on the plywood substrate (Figure 6b). This clearly indicates that the substrate was ignited by the firebrands. On the other hand, there was no second peak in mass loss rate at $s = 30$ mm (Figure 6f). This suggests that the fire did not grow on the substrate surface. At the intermediate spacing $s = 20$ mm, it was observed that fire grew on the plywood substrate after the firebrands extinguished and the second peaks also appeared in mass loss rate (Figure 6d). However, the intensity of fire on a plywood substrate was not consistent in lower flow speeds ($u = 0$ and 0.5 m/s). Under higher flow speed (0.75 m/s), the two repetitive experiments both yield a sustained fire. These observations indicate that the interaction between flaming firebrands became weak as spacing increases and 9 flaming firebrands in this study can cause a sustained fire on a plywood at higher chance at $s \leq 20$ mm. The ambient wind also increases the ignition propensity of the substrate.

In Figure 8, the pyrolyzed area is plotted against spacing and ambient wind speed. The pyrolyzed area was found to be the highest at $s = 20$ mm. Compared to $s = 10$ mm, $s = 20$ mm has a larger inter-brand area for the fire to grow. Compared to $s = 30$ mm, $s = 20$ mm case was able to heat up the substrate more effectively due to the close proximity of the firebrands. In Figure 8b, it was shown that the pyrolyzed area tends to increase with flow speed for all spacing. This is attributed to the tilted flames by strong air flow over the firebrands.

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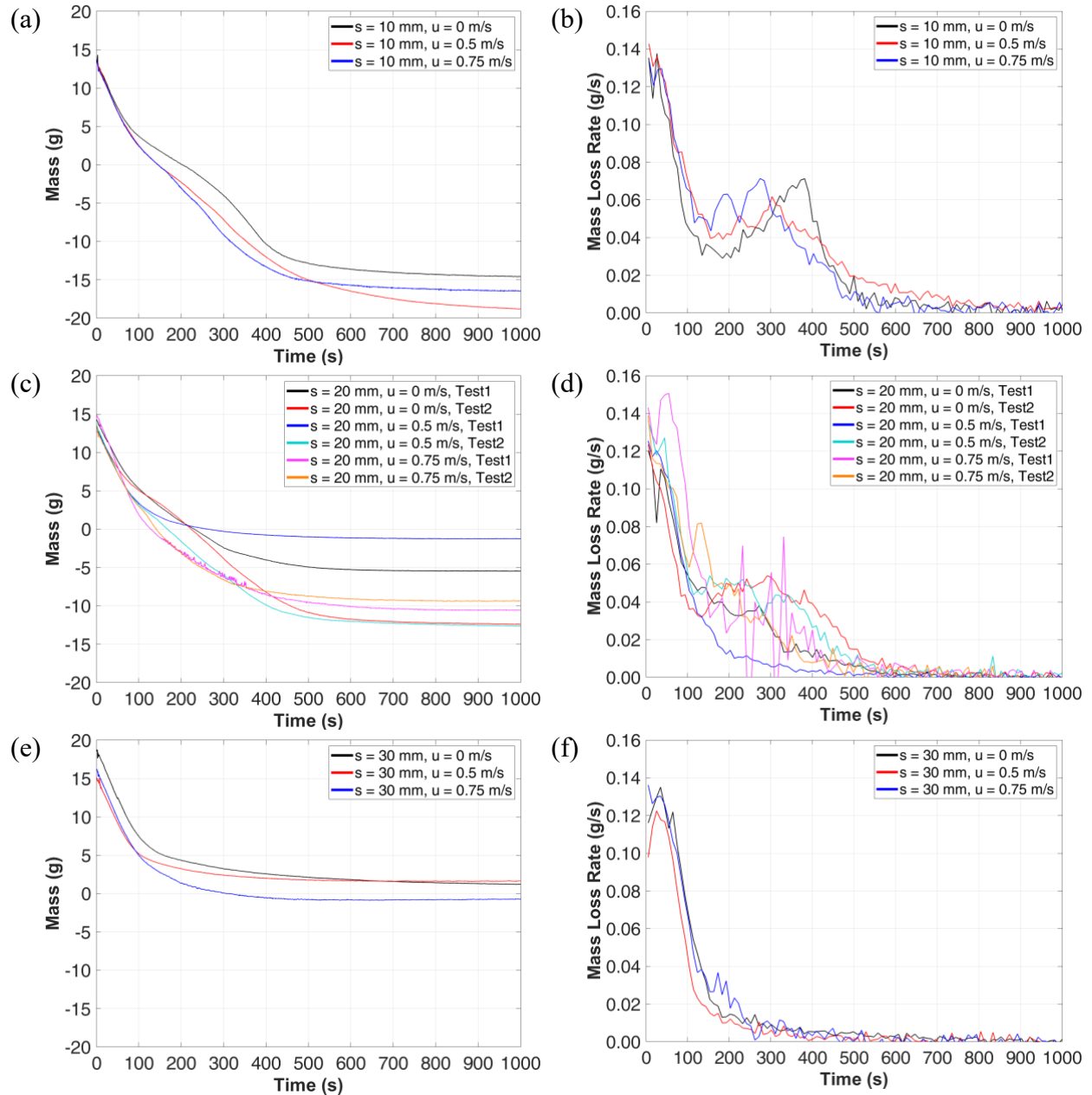


Figure 7. Mass and mass loss rate (a)(b) $s = 10$ mm, (c)(d) $s = 20$ mm, and (e)(f) $s = 30$ mm.

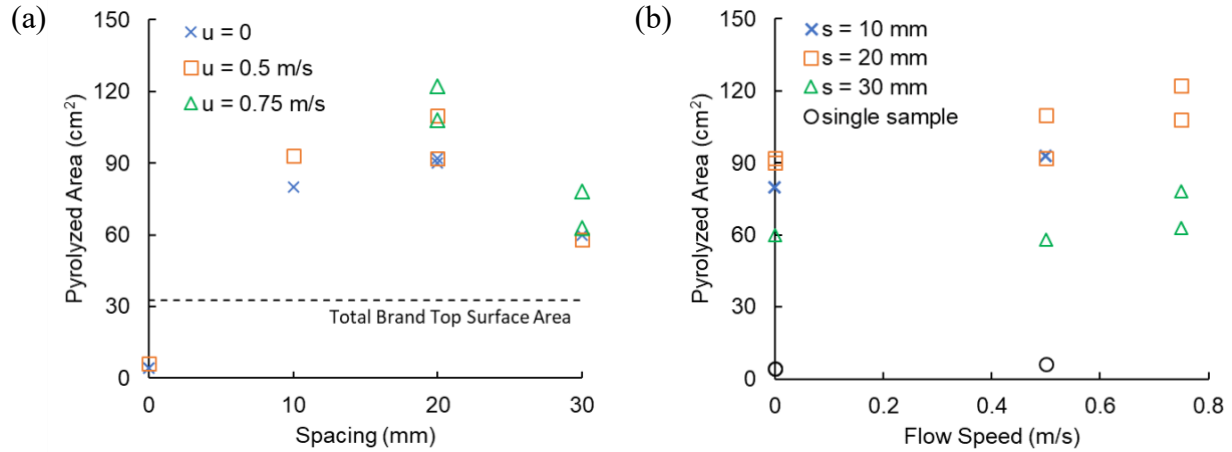


Figure 8. Pyrolyzed area of the plywood substrate at different spacing and different ambient speeds.

4. Conclusions

A 3 by 3 square array of firebrands were dropped on a plywood substrate to investigate the effects of firebrand distribution on the ignition and fire growth on a combustible substrate. The spacing between the firebrands was the main parameter in this study. Different ambient wind speed was also tested to investigate its effects on the likelihood of substrate ignition.

At $s \leq 20$ mm, the plywood substrate was ignited by the firebrands and the fire continued to grow even after all flaming firebrands ceased to burn. On the other hand, a single firebrand or firebrands with 30 mm spacing could not cause a sustained fire on the plywood. This indicates that the narrow spacing between the firebrands significantly increases the likelihood of fire on a building material. When comparing the temperature distribution on the substrate surface, the plywood substrate temperature between the firebrands exceeded the wood pyrolysis temperature at small spacing (e.g., $s = 10$ mm), whereas the plywood heated up to only 130 °C for cases with $s = 30$ mm. It was also found that the wind speed contributes to a wider burning area of the substrate. This is due to the flame tilting in the streamwise direction.

5. Acknowledgements

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6. References

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