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Investigation on the ability of glowing firebrands deposited within crevices to ignite common building materials

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ABSTRACT

A series of experiments was conducted to determine the range of conditions that glowing firebrands may ignite common building materials. The surface temperature of glowing firebrands burning under different applied airflow was quantified using an infrared camera. As the applied airflow was increased, the surface temperature of glowing firebrands was observed to increase. A crevice was constructed using plywood and oriented strand board (OSB) and the angle was varied to investigate the influence that this parameter has on promoting ignition after contact with glowing firebrands. The number of firebrands deposited within the constructed crevices was varied. Single firebrands were unable to ignite the materials used in this study over a range of applied airflows. For the tightest fuel bed angle of 60°, the glowing firebrands deposited on the fuel bed always resulted in smoldering ignition. For plywood, contact with glowing firebrands produced smoldering ignition followed by a transition to flaming ignition. At the fuel bed angle of 90°, no definitive ignition behavior was observed for either material; different ignition criteria (either no ignition or smoldering ignition) were observed under identical experimental conditions. As the fuel bed angle was increased up to 135°, ignition never occurred for both test fuel beds. For a given airflow and fuel bed material, the ignition delay time was observed to increase as the fuel bed angle was increased. A large difference was observed in the ignition delay time for plywood and OSB at a fuel bed angle of 90°. Based on these ignition results, the critical angle for ignition exists between 90° and 135° at a given airflow. These results clearly demonstrate that firebrands are capable of igniting common building materials.

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1. Introduction

The 2007 Southern California fires underscore the difficulty of the problem of structure ignition in wildland–urban Interface (WUI) fires. Firefighting resources were overwhelmed and simply could not handle catastrophic structure ignition in these fires. Similarly, in 2003, WUI fires near San Diego, California, displaced nearly 100,000 people and destroyed over 3000 homes, leading to over $2B in insured losses [1].

Fire risk to WUI communities is currently mitigated by either reducing wildland fuel loading or following a number of home-owner risk reduction practices (e.g., Firewise). The various fuel treatment methods used are based on very limited scientific study, leaving their effectiveness largely unproven, especially with regard to preventing structure ignition. Most of these risk reduction practices follow rule-based and empirically determined checklists that lack testing and are not the result of a coordinated scientific-based effort.

Anecdotal evidence suggests that spotting is the major source of structural ignition in WUI fires. Spot fires are defined as new fires that propagate away from the main fire line due to lofted firebrands. An understanding on how these lofted flaming/glowing firebrands can ignite surrounding fuel beds is necessary to mitigate fire spread in communities [1,2]. The firebrand problem is not trivial and consists of various aspects including the production of combustible products from vegetation and structures, subsequent transport through the atmosphere, and the ultimate ignition of fuels. Most firebrand studies, be they experimental or numerical in nature, have focused on firebrand transport [3–11], attempting to determine the potential spotting distance of firebrands [5,8–10].

One of the purported mechanisms of structure ignition in WUI fires is the trapping of firebrands within small crevices within structures. Unfortunately, very few studies have investigated the range of conditions under which it is possible to ignite these materials by firebrands. Dowling [12] burned wood cribs and the resultant firebrands were collected and deposited into a 10 mm

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gap between the wood bridge members (deck plank and gravel beam). It was observed that 7 g of firebrands was able to produce smoldering ignition of the wood members within the 10 mm gap. The state of the firebrands upon deposition into 10 mm gaps, i.e., glowing or flaming, was not specified.

In early work, Waterman and Takata [13] investigated firebrand impact upon a variety of ignitable materials. The wind speed was altered in these tests. A radiant flux was applied in conjunction with firebrand impact to ascertain material ignitability. Ignition probabilities were reported for the various materials considered. Ignitions were observed from 38-mm-long firebrand (unassisted – no radiant flux) in contact with most of the building materials tested. Firebrands smaller than 38 mm were unable to ignite the building materials considered.

As part of a larger study of various materials, Manzello et al. [14] deposited both glowing and flaming firebrands onto cedar crevices of a fixed angle (90°), but with varying moisture content. Cedar was selected since some types of shingles are actually constructed of cedar. Glowing firebrands were unable to ignite cedar crevices under the conditions tested. A critical flux of three flaming firebrands was required to achieve ignition for multiple flaming firebrands into moist cedar crevices. When the constructed cedar crevice samples were dried, it was observed that only one 50 mm flaming firebrand was required to produce ignition. Additional building materials were not considered in that study and detailed findings regarding critical angles for ignition were not determined.

Clearly, building codes and standards are needed to guide construction of new structures in areas known to be prone to WUI fires in order to reduce structural ignition in the event of a firebrand attack. Detailed understanding is required with regard to common materials found in housing communities. To this end, a crevice was constructed using plywood and oriented strand board (OSB) and the angle was varied from 60° to 135° to investigate the influence that this parameter has on promoting ignition after contact with glowing firebrands. Plywood and OSB are used extensively in the USA as roof-sheathing. Ignition regime maps are presented as a function of the number of deposited firebrands, fuel bed angle, fuel bed moisture content, and applied airflow.

2. Experimental description

Fig. 1 is a schematic of the fire emulator/detector evaluator (FE/DE) that was used as an airflow source; the FE/DE allows airflow rates up to 3 m/s. In addition, this facility is designed to be capable of controlling humidity and ambient temperature as well as airflow velocity. Fig. 2 displays a schematic of the firebrand ignition apparatus that consists of four butane burners and a firebrand mounting probe. This apparatus was installed in the test section of the FE/DE. The butane flow rate is controlled by a metering valve coupled to a solenoid valve. The firebrand or, in the case of multiple firebrand impact, firebrands are held into position and the air pressure is activated, which moves the actuator and

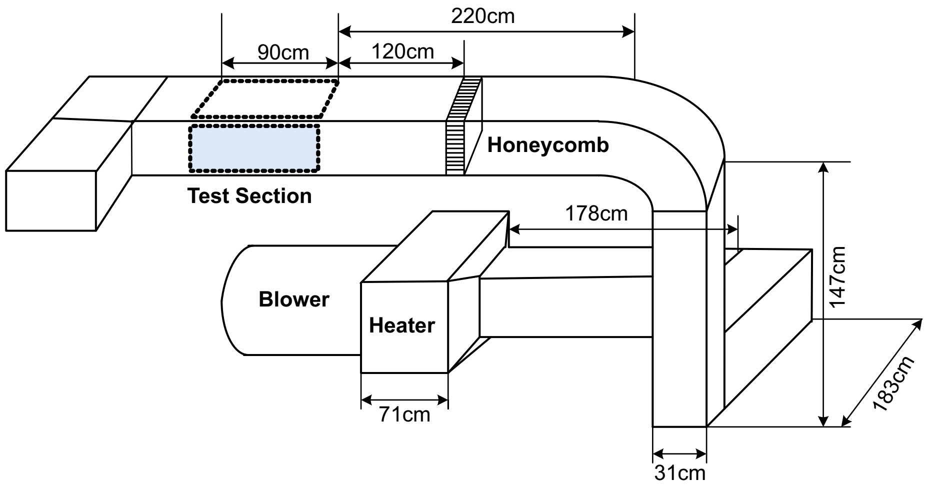

Fig. 1. Schematic of the fire emulator/detector evaluator (FE/DE) used to provide airflow for the ignition tests.

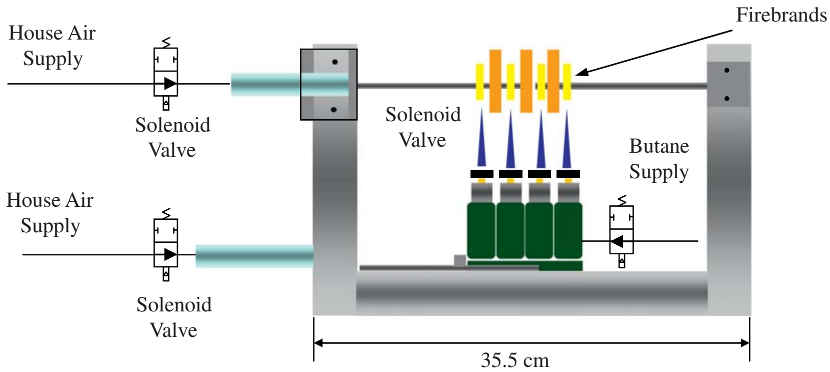

Fig. 2. Schematic of firebrand ignition and deposition apparatus.

clamps the firebrand(s) into position. The retraction of the burner upon ignition and the free-burn time of the firebrands are computer controlled, which ensures repeatability. Each butane burner was designed to be switched on or off, depending on the number of firebrands needed for the particular experiment. Further details of the apparatus, including the FE/DE, are described elsewhere [14–16].

Firebrands were constructed by machining wood into sections of uniform geometry. For the present study, firebrands were simulated as cylinders (10 mm in diameter with a length of 76 mm) determined from the measured firebrand size distributions generated from real-scale tree burns [16]. Ponderosa pine was selected as the wood type for these experiments. After the cylinders were machined, they were stored in a conditioning room prior to the experiments (21 °C, 50% relative humidity) for 2 weeks.

Two different materials were used as test fuel beds for the ignition studies: (1) plywood and (2) oriented strand board. Both these materials are commonly employed as base materials in roofing assemblies in the USA. In the USA, there has been a dramatic shift to the use of OSB; historically plywood was the dominant material used in roof-sheathing [17]. The reasons for this are primarily economic in nature; OSB is manufactured from smaller trees as compared to plywood and consists primarily of wood fragments.

The plywood and OSB pieces were cut into rectangular sections of 206 mm × 88 mm. The thickness of all samples was fixed at 9 mm. The moisture content of these materials was varied from oven dry to 11%. 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 plywood and OSB samples. The firebrand ignition process and release onto the target fuel beds were captured using a CCD camera coupled to a zoom lens.

Firebrands were ignited by exposing them in a vertical orientation, parallel to the burner flow field, for a fixed duration and allowed to free burn. When the firebrands were aligned horizontally, the burners were unable to ignite them completely; the flame would not engulf the entire firebrand. Under airflow conditions, the firebrands were ignited under low flow conditions and the airflow was ramped up as soon as the ignition process was over. The ignition time for the 10 mm firebrands was 70 s. These ignition times were selected in order to completely engulf the firebrand in flame. Under no airflow conditions, the firebrand remained in a flaming state. When airflow was introduced, the airflow blew off the envelope flame from the leading edge of the firebrand and gradually blew the flame off the backside of the firebrand. After the flame was blown off, a glowing firebrand resulted. A similar result was observed using Douglas-Fir cylinders [16]. The ignition propensity of the plywood and OSB fuel beds was determined only under conditions of glowing firebrand deposition.

When the burning firebrands were deposited onto the fuel beds, experiments were performed only under conditions of an airflow (1.3 and 2.4 m/s); it is not expected that the flow conditions would be quiescent as firebrands impact fuel beds during wind-blown WUI fires. The airflow was quantified using a hot-wire anemometer. It is important to note that the ambient temperature inside the duct of the FE/DE was monitored and fixed at 21 °C for all experiments reported here. Ambient temperature conditions are known to influence ignition outcomes for fuel beds [14–16].

3. Results and discussion

Fig. 3 displays the heat and mass transfer processes that take place at the fuel bed in contact with a glowing firebrand in this study. The deposited firebrands heat up the surface, resulting in the production of pyrolysates. As a result, flammable air/fuel mixtures are formed above the fuel bed. Continued heat supplied from the firebrands contributes to exothermic gas-phase reaction, leading to ignition. The net heat flux, q''_{net}, to the fuel bed from the impinged firebrands is given as

$$q''_{net} = q''_{FB} - (q''_{conv} + q''_{rad} + \dot{m}''L_v) \tag{1}$$

where q''_{FB} is the heat flux from the firebrands, q''_{conv} is the convective heat flux, q''_{rad} is the radiative heat flux, $\dot{m}''$ is the mass loss rate per unit area, and L_v is the heat of gasification.

Ignition results obtained from all glowing firebrand experiments are summarized in Table 1. Five identical experiments were repeated for each case. The following definitions were used: SI = smoldering ignition; FI = flaming ignition; and NI = no ignition. Ignition was observed only when the plywood and OSB samples were oven dried. No ignition was observed for samples held at 11% moisture content. This can be explained by the higher

Table 1
Glowing firebrand ignition data.

Air flow (m/s)	Number of firebrands	Fuel bed angle (°)	Fuel bed material	Ignition type
1.3	4	60	Ply wood	**NI**
2.4	4	60	Ply wood	**SI to FI**
2.4	4	60	OSB	**SI** or **SI to FI**
2.4	3	60	Ply wood	**NI** or **SI**
2.4	3	60	OSB	**NI** or **SI**
2.4	2	60	Ply wood	**NI**
2.4	2	60	OSB	**NI**
2.4	4	90	Ply wood	**NI** or **SI**
2.4	4	90	OSB	**NI** or **SI**
2.4	4	135	Ply wood	**NI**
2.4	4	135	OSB	**NI**

NI: No ignition; SI: smoldering ignition; FI: flaming ignition; SI to FI: transition from SI to FI.

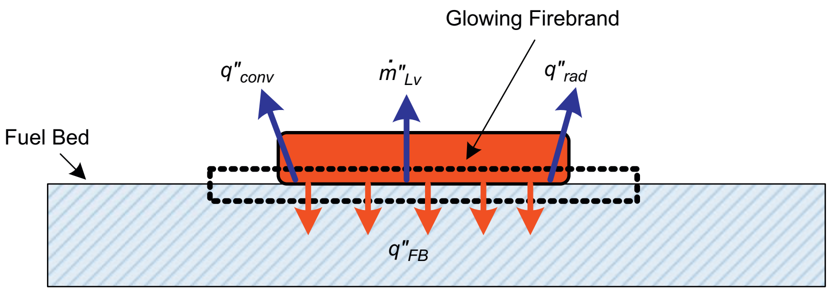

Fig. 3. Heat and mass transfer process around the firebrand deposited onto the fuel bed.

heating value and thermal inertia of the samples. The moisture embedded in the samples reduces the thermal efficiency since the heating and gasification of water consume additional energy. Consequently, this will result in the high value of heat of gasification in Eq. (1), reducing the net heat flux to the fuel bed. The moisture content is also known to affect the room-temperature density of the fuel bed material, the thermal conductivity, and the heat capacity, and thus the thermal inertia. A high thermal inertia value for a wet fuel bed increases the thermal resistance to changes in temperature, reducing ignitibility.

As tabulated in Table 1, for both plywood and OSB fuel beds, NI was observed at the airflow of 1.3 m/s for the tightest fuel bed angle of 60°, even when four firebrands were deposited. When the airflow was increased to 2.4 m/s for the same fuel bed angle, ignition was observed to occur. For a fixed fuel bed angle, the increased airflow around the firebrands results in a larger convective heat loss at the fuel bed, eventually reducing the q''_{net} to the fuel bed. However, at the same time, increased airflow will influence the concentration of oxidizer and the mixing of fuel and oxidizer in the gas stream, which may lead to an increase in the firebrand temperature. This will lead to the increase in the reaction rate and thus q''_{FB}.

To quantify the influence of an airflow on firebrand temperature, the surface temperature of a single glowing firebrand exposed to an airflow was measured. The authors are not aware of any prior studies that have attempted to measure the temperature of glowing firebrands. To accurately measure the surface temperature of a glowing firebrand, an infrared camera was used in the present study. The infrared measurement has a significant advantage over thermocouple measurements. Thermocouple surface temperature measurements in the presence of an airflow require temperature correction that can introduce great uncertainties. The temperature correction is usually performed by evaluating heat losses around the thermocouple bead. For this correction, accurate determinations of thermophysical properties of the thermocouple bead such as specific heat, thermal conductivity, density, and emissivity are needed. In addition, the thermocouple bead in contact with the glowing firebrand is not fully exposed to airflow during experiments but is partially exposed. Therefore, the thermocouple bead cannot be treated as a sphere and this makes determining the convective heat transfer coefficient difficult.

Even though the infrared measurements may avoid the necessity of temperature correction, the emissivity of a given object should be carefully determined to assess the surface temperature. For glowing firebrands, most thermal radiation originates from charred areas, which mostly comprise carbon. The emissivity of wood char has been assumed to be similar to that of carbon, which ranges from 0.8 to 1.0 [18,19]. However, the actual emissivity of wood char formed (or being formed) during combustion can be affected by the ash layer deposited on the surface, resulting in lowering the overall emissivity. Therefore, the emissivity of char formed on the surface of the glowing firebrand was experimentally determined in the present study. The surface temperature of charred area on the glowing firebrand was simultaneously measured using both the thermocouple and the infrared camera in a quiescent environment. The glowing (charred) area close to the thermocouple bead was imaged using the infrared camera and the emissivity was then adjusted until the temperature readings on the infrared camera converged to those registered by the thermocouple measurements. The firebrand was ignited using the same burner used in the experiments and was allowed to burn in the quiescent environment for 25 s. The envelope flame diminished, resulting in a glowing firebrand, and the surface temperature was measured at this point. Fig. 4

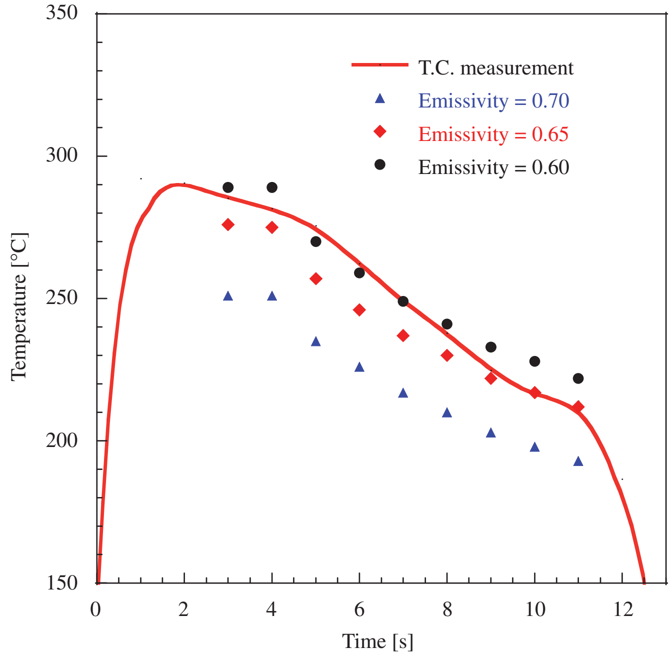

Fig. 4. Measured surface temperatures of a glowing firebrand as a function of time.

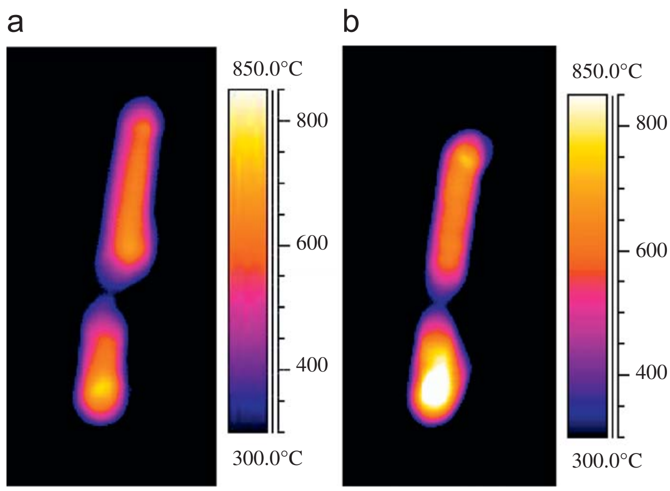

Fig. 5. IR images of the glowing firebrand exposed to two different airflows: (a) 1.3 m/s and (b) 2.4 m/s.

displays the surface temperatures of the charred area in a quiescent environment as a function of time. As shown in the figure, temperatures measured by the infrared camera approach those measured by the thermocouple as the emissivity set on the camera was reduced from 0.7 to 0.6. Based on these experimental results, the emissivity of the glowing firebrand in the present study was set to 0.6, which is in good agreement with that of wood char determined by Suuberg et al. [20]. In our IR measurements, an uncertainty of $\pm 10\%$ in the given ε ($= 0.6$) was found to cause an error of temperature of only $\pm 13\,°C$.

Fig. 5 displays the IR images of the glowing firebrand exposed to the airflow of 1.3 and 2.4 m/s. Note that a relatively low-temperature regime observed in the middle of a glowing firebrand is owing to the interference with holders (that secure the firebrand during measurements). The images were obtained 1.0 s after the envelope flame was blown off and glowing began. The results reveal that there is approximately 98 °C difference in the maximum surface temperature of the glowing firebrand between the two different airflow cases. To quantitatively analyze the results, the average surface temperatures for two cases are plotted as a function of time in Fig. 6. The average surface temperatures were obtained from three different glowing firebrands under identical experimental conditions and evaluated by considering the sum of maximum and minimum surface temperatures divided by 2. As shown in the figure, the measured average surface temperatures begin to decrease with time for both cases. These results clearly indicate that the higher airflow induces a higher surface temperature of glowing firebrands, which results in an increase in q''_{FB} and thus an increase in q''_{net}.

In the present study, q''_{FB} was estimated by considering the heat transfer between a glowing firebrand across an airflow:

$$q''_{FB} = \varepsilon\sigma(T^4_{surf} - T^4_{amb}) + h(T_{surf} - T_{amb}) \quad (2)$$

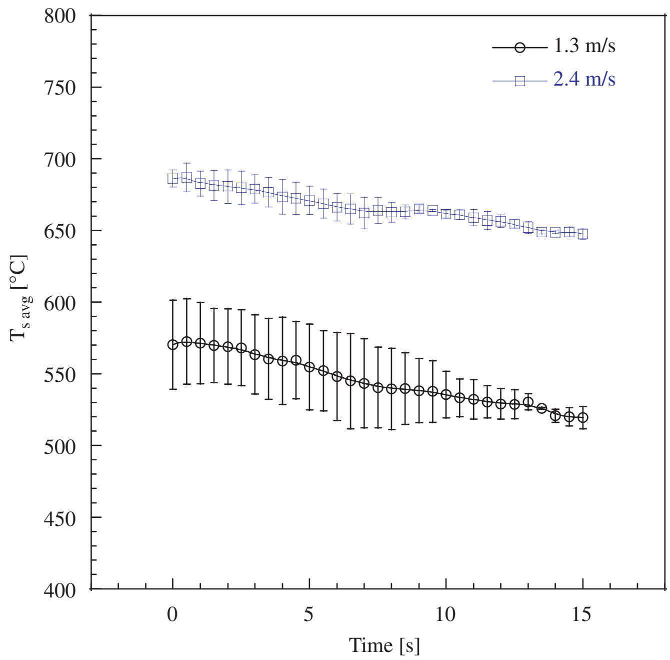

Fig. 6. Average surface temperatures of the glowing firebrand as a function of time. (Error bar indicates the standard deviation obtained from 3 different experiments carried out under the same experimental conditions.)

$$h = Nu\frac{k}{D} \quad (3)$$

where ε is the emissivity of a glowing firebrand, σ is the Stefan–Boltzmann constant, T_{surf} and T_{amb} are firebrand surface temperature and ambient temperature, h is the convective heat transfer coefficient, k is the thermal conductivity, and D is the diameter of a firebrand. Nusselt number was obtained by assuming that a firebrand has a cylindrical geometry and is defined as [21]

$$Nu = 0.3 + \frac{0.62Re^{1/2}Pr^{1/3}}{[1+(0.4/Pr)^{2/3}]^{1/4}}\left[1+\left(\frac{Re}{282,000}\right)^{5/8}\right]^{4/5} \quad (4)$$

where Re is Reynolds number and Pr is the Prantl number. The calculated heat flux was 23.4 kW/m^2 for the glowing firebrand exposed to the airflow of 1.3 m/s and 34.2 kW/m^2 for that exposed to an airflow of 2.4 m/s.

In the previous experiment performed by Bilbao et al. [22], a constant heat flux from a cone heater was applied to a 19-mm-thick *Pinus Pinaster* sample (which contains a water content of 9% on a dry basis) with the airflow present. To produce ignition in their experiment, a minimum heat flux of 25 kW/m^2 was required at an airflow of 1.0 m/s and 28 kW/m^2 at an airflow of 2.0 m/s. Despite some differences in the experimental conditions, their results are comparable to the present experiments. In both experiments, the heat flux applied to the fuel bed, i.e., q''_{net}, will be reduced mainly due to the convective heat loss induced by the airflow. The major difference is the fact that the q''_{net} in the present experiments further decreased with time due to reductions in the char oxidation rate (which is a main heat source to sustain the surface glowing of the firebrands). This may result in NI at an airflow of 1.3 m/s in the present experiments. In the previous experiment [22], the minimum heat flux to cause ignition was observed to increase with the airflow. Good agreement with this trend was observed in that in the present study a higher heat flux of 34.2 kW/m^2 at an airflow of 2.4 m/s caused ignition. This heat flux is higher than the critical heat flux for various wood materials investigated previously in a quiescent environment, which ranges from 4 to 12 kW/m^2 depending on experimental conditions.

The fuel bed angle was varied from 60° to 135° to further examine the relative importance of this parameter on q''_{net}; the airflow was set to 2.4 m/s. A careful review suggested that there have been no studies to investigate the influence of various fuel bed angles on q''_{net}. Fig. 7 shows the digitized images of the glowing firebrands deposited on the plywood fuel bed at 60° and 135°. For the tightest fuel bed angle of 60°, the glowing firebrands

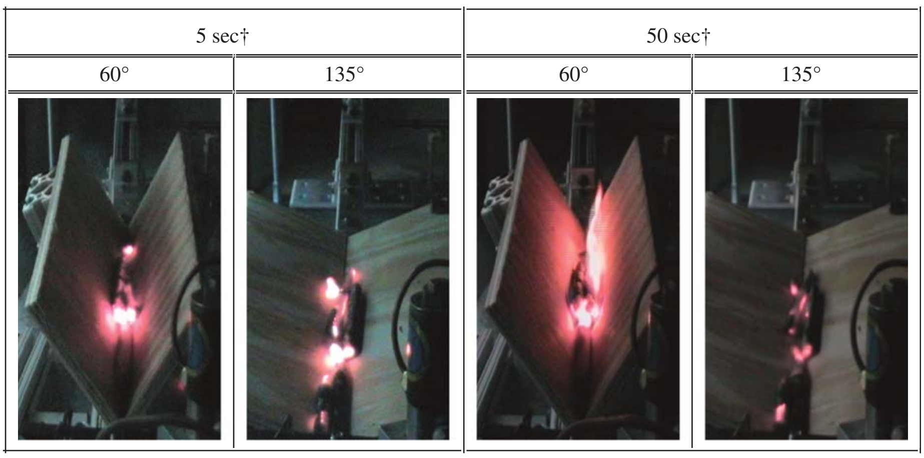

Fig. 7. Glowing firebrand impingement onto the fuel bed with different angles. *Note*: † indicates the time elapsed after all impinged firebrands are stationary on the fuel bed.

Table 2
Averaged delay time in intense smoke generation for four firebrand impingement experiments at the airflow of 2.4 m/s.

Fuel bed angle (°)	Fuel bed material	Delay time (s)
60	Ply wood	5
	OSB	7
90	Ply wood	32
	OSB	65
135	Ply wood	–
	OSB	–

deposited on the fuel bed always resulted in SI for both test fuel beds. For plywood, contact with glowing firebrands produced SI followed by a transition to FI. For OSB, under the same conditions, the SI was always observed, but the SI to FI transitions did not always occur. At a fuel bed angle of 90°, no definitive ignition behavior was observed for either material; different ignition criteria (NI and SI) were observed under identical experimental conditions. As the fuel bed angle was increased to 135°, ignition never occurred for both test fuel beds. Based on these ignition results, the critical angle for ignition exists between 90° and 135° at a given airflow. For completeness, these results required the deposition of four firebrands.

In these experiments, intense smoke generation was defined to be the initiation of SI; the observed delay in smoke generation was interpreted as the ignition delay time. The observed ignition delay time for four firebrand impingement experiments performed at the 2.4 m/s airflow is listed in Table 2. For a given airflow and fuel bed material, the ignition delay time was observed to increase as the fuel bed angle was increased. A large difference was observed in the ignition delay time for plywood and OSB at a fuel bed angle of 90°. The ignition time for thermally thick materials is known to be proportional to the room-temperature density of the material and inversely proportional to the square of the net heat flux to the fuel bed [23,24].

$$t_{ig} \propto \frac{\rho}{q''^{2}_{net}} \tag{5}$$

Therefore, the observed ignition results directly indicate that the increased q''_{net} from the firebrands was transferred to the fuel bed for the tightest fuel bed angle, resulting in a short ignition time (for fixed airflow, fixed number of deposited firebrands, fixed fuel bed material). The increase in q''_{net} with decreased fuel bed angle may be attributed to the arrangement of glowing firebrands on the fuel bed.

The arrangement of deposited firebrands greatly affected the net heat flux to the fuel bed (for a fixed airflow and fixed number of deposited firebrands). For example, although an individual glowing firebrand is assumed to produce the same quantity of heat flux, the heat delivered to the fuel bed will be altered due to the arrangement between glowing firebrands and the fuel bed. At a tighter fuel bed angle, it is easier for the glowing firebrands to stack together. The firebrands that stack together at the tighter fuel bed angle will irradiate more heat flux on a given target area, heating the area in contact with firebrands more effectively.

As a simple test, under fixed airflow conditions and fixed fuel bed angle, the direct way to diminish the q''_{net} is to reduce the number of glowing firebrands. Experimental results summarized in Table 1 clearly show the influence of the number of glowing firebrand on the ignition. When two glowing firebrands were deposited, an ignition event for the fuel bed angle of 60° was not observed. When three firebrands were deposited, either NI or SI was observed. These results imply that the heat flux from three firebrands is near the critical heat flux for ignition. It is also believed that the heat flux from three firebrands at a fuel bed angle of 60° is in a similar range with that from four firebrands at a fuel bed angle of 90° since both cases produce similar ignition criteria, namely NI or SI. The deposition of three glowing firebrands results in a direct reduction in the q''_{FB} compared to the deposition of four glowing firebrands. However, this reduction in the firebrand heat flux is compensated by decreased radiative heat losses as the fuel bed angle is reduced to 60°. As a result, the deposition of three glowing firebrand produces SI despite reductions in the q''_{FB}.

4. Summary

The present investigation reported on experiments conducted to determine the range of conditions under which glowing firebrands may ignite common building materials. Firebrands were ignited by exposing them in a vertical orientation, parallel to the burner flow field, for a fixed duration and allowed to free burn. When an airflow was introduced, the airflow blew off the envelope flame from the leading edge of the firebrand and gradually blew the flame off the backside of the firebrand. After the flame was blown off, a glowing firebrand resulted. The glowing firebrands were subsequently deposited onto samples of plywood and oriented strand board.

For an airflow of 1.3 m/s, ignition was not observed under any conditions. To quantify the influence of an airflow on firebrand temperature, the surface temperature of a single glowing firebrand exposed to an airflow was measured using the infrared camera. Measured average surface temperatures suggest that the firebrand temperature did increase as the airflow was increased. Thus, it was postulated that the higher airflow induced a higher surface temperature of the glowing firebrands, which resulted in an increase in q''_{FB}, which will produce and increase in q''_{net}. This resulted in SI under the same experimental conditions at an airflow of 2.4 m/s and NI at an airflow of 1.3 m/s.

The fuel bed angle was varied from 60° to 135° to further examine the relative importance of this parameter on the q''_{net}; the airflow was set to 2.4 m/s. For the tightest fuel bed angle of 60°, the glowing firebrands deposited on the fuel bed always resulted in SI for both test fuel beds. For plywood, contact with glowing firebrands produced SI followed by a transition to FI. At the fuel bed angle of 90°, no definitive ignition behavior was observed for either material; different ignition criteria (NI and SI) were observed under identical experimental conditions. As the fuel bed angle was increased up to 135°, ignition never occurred any more for both test fuel beds. For a given airflow and fuel bed material, the ignition delay time was observed to increase as the fuel bed angle was increased. A large difference was observed in the ignition delay time for plywood and OSB at a fuel bed angle of 90°. Based on these ignition results, the critical angle for ignition exists between 90° and 135° at a given airflow. These results clearly demonstrate that firebrands are capable of igniting common building materials.

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