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Role of accumulation for ignition of fuel beds by firebrands

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ABSTRACT

Large outdoor fires are one of the prominent fire problems in the world. Spot fires, caused by firebrands, are known as a key mechanism of rapid fire spread. Firebrands ignite unburned fuels far ahead of the fire front. In large outdoor fires, firebrands are thought to accumulate and ignite unburned fuel which cannot be ignited by a single firebrand. Experiments are performed to investigate the ignition behavior of fuel beds with changing fuel moisture content (FMC) and wind speed. It was found that accumulated firebrands could cause ignitions on fuel beds with high FMC and the upper limit of FMC for ignition increased from 6 m/s to 8 m/s.

1. Introduction

Large outdoor fires, such as wildfires, Wildland-Urban Interface (WUI) fires, urban fires, and informal settlements fires, are one of the prominent fire problems in the world [1]. Spot fires, caused by firebrands, are known as a key mechanism of rapid fire spread as indicated in post-fire investigation in the USA [2] and Australia [3]. Firebrands are generated from burning vegetation or structures, lofted, and ignite unburned vegetation and structures far from the initial fire source [4]. Wind plays an important role in firebrand transport, as well as subsequent ignition processes induced by firebrands [4]. With wind, firebrands may fly far and cause multiple ignitions at various locations, resulting in rapid fire spread [2,3]. Research on firebrands could be divided into four areas – firebrand generation, firebrand transport, deposition, and ignitions by firebrands [4]. For a long time, most research on firebrands has been focused on firebrand transport [4]. These are reviewed briefly.

The flight trajectory and the burn out time of single wood pieces was studied theoretically and experimentally in a wind tunnel [5]. Spherical-shaped or cylindrical-shaped wood pieces with different initial size were investigated. It was found that firebrands fly with almost terminal velocity. In another study, the trajectories of a firebrand in a turbulent swirling natural convection plume was studied theoretically and experimentally [6]. It was reported that the shape of a firebrand affected the trajectories. Firebrand trajectories were modelled assuming lofting by line thermals [7]. The burning rate of a firebrand was considered in this model, while there was no experimental data to validate the model. Bark from trees were also used to study the trajectories, changing the initial size and combustion state [8]. It was found that the combustion state of a firebrand would affect its trajectory significantly. More recently, a coupled-physics fire model, HIGRAD/FIRETEC was used to model disk-shaped and cylinder-shaped firebrands in different combustion states [9]. The effect of a non-steady inhomogeneous plume, seen in real fires, on firebrand trajectories were investigated. It was suggested that the assumption that firebrands fly with their terminal velocity underestimates the travel distance. A shower of non-burning pieces was used as surrogate of firebrands to study the firebrand behavior under wind [10]. It was found that the maximum rise height has effects on the downwind location of firebrands. While research on firebrand transport is considered more mature than research on ignition by firebrands, studies are still relatively limited to single burning pieces or a shower of non-combusting pieces.

More research on firebrand generation and ignitions by firebrands has been performed recently due to the overwhelming number of large outdoor fires in the world [4]. Mechanisms of ignitions by firebrands have yet to be understood completely. Conditions of recipient fuel beds, firebrands, and ambient environments have to be taken into consideration. Fuel moisture content (FMC) is considered one of the primary factors in ignition and fire spread of wildland or WUI fuels [11]. Upon landing on fuel beds, firebrands may be in a flaming or glowing state of combustion. Ignitions by a single flaming firebrand or a single glowing firebrand are often investigated in laboratory conditions, as these types of experiments are simple to undertake [4].

Pertinent literature is reviewed briefly here on ignition by firebrands. A series of experiments was performed to study ignition on different mulch beds by two sizes of firebrands with different size and combustion state [12]. Fuel moisture content (FMC) was either oven-dried or 11% and experiments were performed under three different wind speeds. Hardwood mulch beds with 11% FMC were never ignited by firebrands in this study. In experiments with two sizes of cylindrical shaped fire-

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brands, hardwood mulch beds with 11% FMC were not ignited by one or four firebrands, regardless of firebrands' combustion state (flaming or glowing) [13]. The time to ignition was not measured in this experimental series, and the focus was on whether smoldering or flaming ignition occurred or not. Flammability of mulch beds commonly seen in Europe by a firebrand was studied [14]. One was 'fuel beds tests', which was more relevant to this study, investigating time to ignition of mulch beds by a glowing 'standard' firebrand with different FMC and bulk density by changing fuel beds. Mulch beds in that study were mostly litters (leaves). In fuel beds tests, they found correlations among the time to ignition, FMC, and bulk density, with FMC and bulk density as independent variables, which differ depending on fuel beds. It was found the adjusted standard deviation (R^2) of the multiple regressions for time to ignition for all fuel beds tested and pine fuel beds was low. Another research study on a single glowing firebrand ignition on pine needles suggested a new correlation between ignition time and FMC [15]. A firebrand made from 2 cm x 2 cm x 1 cm cubic wood was able to ignite pine needle beds with 65% FMC. A theoretical approach of heat transfer between pine needles and a single glowing firebrand under different FMC was supported by experiments under a 3 m/s wind. The correlation showed a linear relationship between FMC and a square root of the ignition time. Firebrand ignition tests on pine straw, shredded hardwood, pine bark nuggets, and pine bark were conducted under no wind [16]. The standard wood cribs were used as firebrands for this test. The shredded hardwood mulch, as well as pine bark, was ignited by the biggest wood cribs (30.48 cm x 30. 48 cm x 6. 35 cm) used in this study while the other two kinds of mulch were unable to get ignited by the smaller wood cribs.

Another research on fuel bed ignitions by a firebrand made from barks or cones indicated it was not possible to ignite fuel beds by glowing firebrands [17]. The smoldering ignition of coastal redwood sawdust by a glowing firebrand was investigated by changing FMC and the size of firebrands. The larger firebrands could ignite fuel beds with FMC up to 40%. It was found that the 3.17 mm diameter glowing firebrand could not ignite the dry fuel bed [18]. An accumulation of glowing firebrands is also a key to ignitions while past experiments on ignitions mainly focus on a single firebrand. It is especially important with fuel beds with high FMC, shown in experiments in a wind tunnel facility. It was shown that the wind enhanced the ignition of fuels by firebrands [19]. Even though wind plays an important role for the firebrand ignitions in actual large outdoor fires, wind effect was rarely considered in nearly all prior studies in the literature. It is important to take the transport phenomena of firebrands, rather than firebrands deposition only, into consideration when investigating ignition phenomena.

In this study, a detailed investigation was performed in order to understand the effect of the accumulation of firebrands on ignition of fuel beds. The effect of wind speeds as well as FMC on ignition behavior was investigated.

2. Experimental description

Experiments were performed in a wind tunnel facility housed at the Building Research Institute (BRI), using the NIST continuous-feed firebrand generator (NIST Dragon) (see Fig. 1). The NIST Dragon is able to produce firebrand showers often seen in real wildland or WUI fires and the size of firebrands was matched with past studies [20]. Douglas-fir wood pieces with the size of 7.9 mm x 7.9 mm x 12.5 mm were used to generate firebrands from the NIST firebrand generator. The size and mass of firebrands produced in this study is similar to the those from trees [21]. The size and the mass of firebrands were measured via separate set of experiments, collected by water pans. The data of the projected area and the mass of firebrands is provided in Fig. 2. The average projected area and the average mass of firebrands are 1.0 cm^2 and 0.05 g with uncertainties of ± 10% for 6 m/s 8 m/s. The difference of the average projected area or the mass of firebrands under 6 m/s and 8 m/s are negligible; both being within uncertainties. As the ignition behavior by firebrand accumulation is the target of this study, these wood pieces were selected as the initial size before combustion are intentionally uniform in size.

Wood pieces of 200 g are fed into the NIST Dragon every 15 s from the feeding system (total 800 g per a minute). The firebrand flux at the exit is 342 $/m^2$ s. The uncertainty of firebrand flux is ± 10%. Two gates are used to prevent combustion into the feeding storage area from the NIST Dragon; when one gate is open, the other gate remains closed.

Wood pieces were ignited by propane burners and lofted as the density becomes less. Eventually firebrands were ejected from the exit of the NIST firebrand generator with the wind provided by the blower from the bottom and the average wind speed at the exit is 3.0 m/s. Fuel beds, commercially available shredded hardwood mulch with the bulk density of 0.25 g/cm^3 ± 0.02 g/cm^3 (Fig. 3), were placed downwind at 3.25 m from the NIST firebrand generator. The dimensions of fuel beds were 1.22 m x 1.22 m x 0.051 m. Fuel moisture content (FMC) was calculated by using dry-basis methods ($FMC = (m_{wet} - m_{dry})/m_{dry}$). FMC was varied from 0% (oven-dry condition) to 100%. The two applied wind speeds were selected for the experiments, namely, 6 m/s and 8 m/s.

These wind speeds are selected as they are within the range of those observed in actual large outdoor fires such as Angora fire in 2007 [22] or Beppu-city fire in 2010 [23]. Not all firebrands may land on the fuel beds. Firebrands that arrived were observed to land on the fuel beds uniformly. Firebrand accumulation occurred due to firebrand movement after landing on the fuel beds. The arrival firebrand flux under 6 m/s and 8 m/s are 7.36 $/m^2$ s and 6.18 $/m^2$ s respectively.

The present study focuses on individual spot fires in fuel beds rather than overall fuel bed ignition process [19]. The experiments were performed with and without wall assemblies, in both cases with fuel beds. The experiments without wall assemblies were performed simply to compare the effect of the existence of the corner assembly, which was found to have little effect for time to ignition [19]. The time to ignition was measured for each spot fire and the number of firebrands involved with each spot fire was determined from video analysis (30 frames per a second). Time 0 was defined as the time when a first firebrand landed on the targeted area. The target areas were chosen as the locations where firebrands accumulated. The area considered for accumulation was considered as the area where a firebrand landed at the same place or next to each other. The number of firebrands landing on the targeted area was counted until smoldering or flaming ignition was observed.

3. Heat transfer between firebrands and fuel beds

Considering heat transfer processes between the firebrand, the surrounding fuel beds, the ambient, and assuming the fuel beds ignite upon reaching the smoldering ignition temperature (for simplicity), the expression can be written as:

$$Q_{fb} = Q_{rad} + Q_{conv} + Q_{evap} + Q_{heat} \tag{1}$$

Here, Q_{fb}, Q_{rad}, Q_{conv}, Q_{evap}, and Q_{heat} is the total heat released from firebrands, the radiative heat loss to the ambient, the convective heat loss to the ambient, the energy required to dry the fuel bed, and the energy required to heat the fuel beds to the smoldering ignition temperature.

Q_{rad}, and Q_{conv} can be described as follows:

$$Q_{rad} = \in \sigma A_{ambient} \int_{t_0}^{t_{ig}} \left(T_{firebrand}^4 - T_\infty^4 \right) dt \tag{2}$$

$$Q_{conv} = h_{conv} A_{ambient} \int_{t_0}^{t_{ig}} \left(T_{firebrand} - T_\infty \right) dt \tag{3}$$

where $T_{firebrand}$ is the firebrand temperature which is changing with time, T_∞ is the ambient temperature, t_0 and t_{ig} are time when the first firebrand landed on the targeted area of fuel beds, and time when the ignition was observed respectively, ε is the emissivity factor, σ is Stefan-Boltzmann constant, h_{conv} is the convective heat coefficient and $A_{ambient}$ is the firebrand surface area exposed to the ambient. It is common to

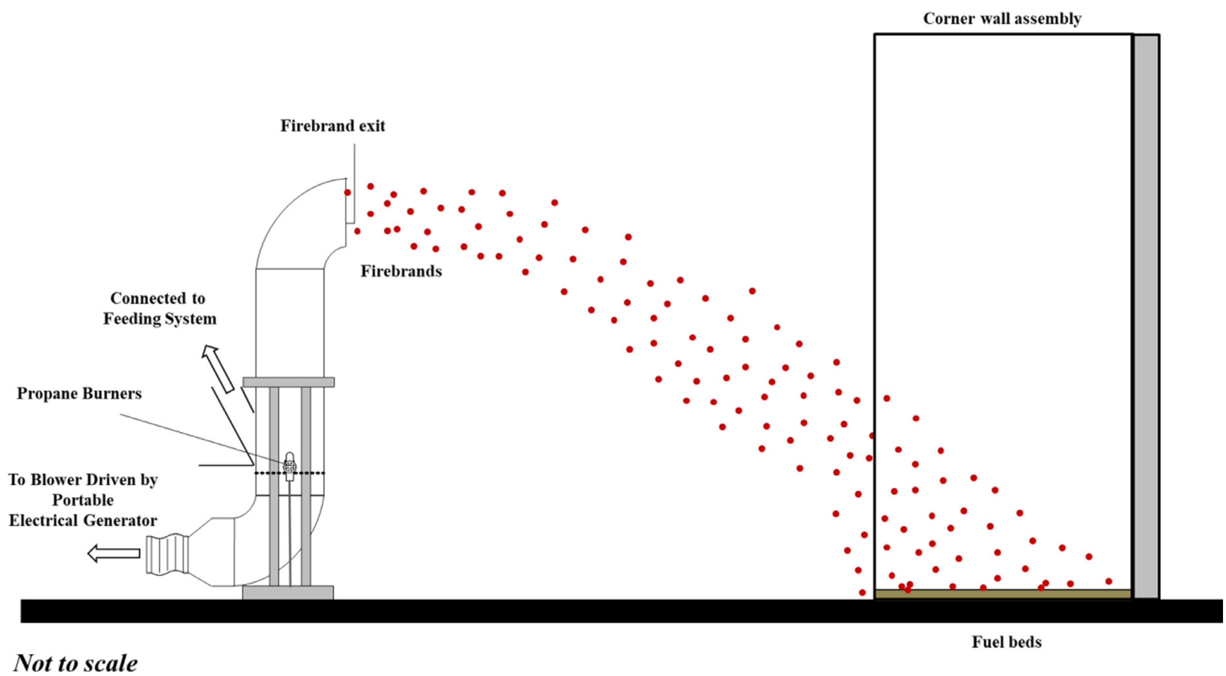

Fig. 1. Schematic of the NIST continuous-feed firebrand generator and experimental settings.

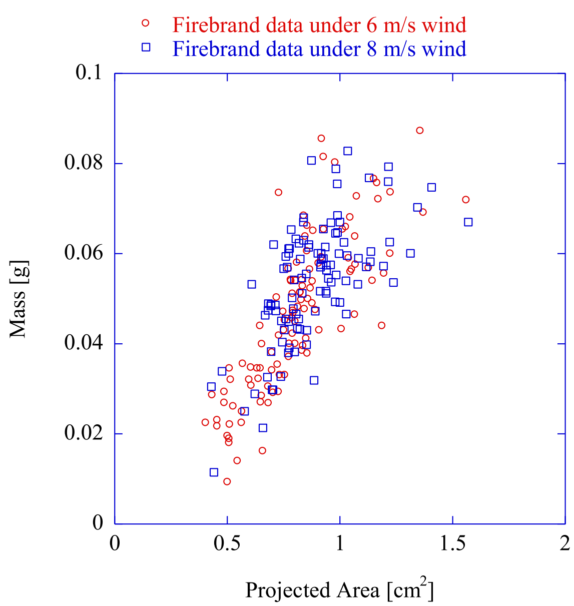

Fig. 2. Characteristics of firebrands under 6 m/s and 8 m/s.

Fig. 3. Image of fuel beds, shredded hardwood mulch, in this study.

assume a firebrand changes mass due to combustion, not the shape, for simplicity. Assuming the temperature of firebrands, $T_{firebrand}$, is constant, Eqs. (2) and (3) could be expressed as follows:

$$Q_{rad} = \in \sigma \left(T_{firebrand}{}^{4} - T_{\infty}{}^{4}\right)\left(t_{ig} - t_{0}\right) A_{ambient} \tag{4}$$

$$Q_{conv} = h_{conv}\left(T_{firebrand} - T_{\infty}\right)\left(t_{ig} - t_{0}\right) A_{ambient} \tag{5}$$

This assumption was made for simplicity, and future considerations may be needed. More discussion is provided later regarding model assumptions.

The energy required to dry the fuel bed, Q_{evap} is described as follows:

$$Q_{evap} = FMC\ \Delta H_{vap} m_{dry,\ fuel} \tag{6}$$

where ΔH_{vap} is the latent heat of evaporation, and $m_{dry,fuel}$is the mass of dry fuel beds which is involved with ignition. Therefore:

$$m_{dry} = \rho_{dry,\ fuel} V_{fuel} \tag{7}$$

where $\rho_{dry,fuel}$ is the density of the fuel beds, and $V_{dry,fuel}$ is the volume of fuel beds. Assuming the ignition occur close to the firebrand locations within the thickness of δ, the volume may be assumed as:

$$V_{fuel} \approx A_{embedded}\ \delta \tag{8}$$

then

$$Q_{evap} \approx FMC\ \Delta H_{vap} \rho_{dry,\ fuel} A_{embedded}\ \delta \tag{9}$$

where $A_{embedded}$ is the firebrand surface area which exposed to fuel beds, and δ is the thickness of fuel beds involved with ignition.

Assuming the firebrands ignite the fuel beds when the temperature of the fuel beds reaches the ignition temperature, T_{ig} from the initial temperature, T_0:

$$Q_{heat} = \rho_{dry,\ fuel}\, c_{fuel}\, V_{fuel}\left(T_{ig} - T_0\right) \approx \rho_{dry,\ fuel}\, c_{fuel}\, A_{embedded}\, \delta \left(T_{ig} - T_0\right) \tag{10}$$

where c_{fuel} is the specific heat capacity of fuel.

As firebrands randomly land on the targeted area of the fuel beds and eventually burned out:

$$Q_{fb} = \int_{t_0}^{t_{ig}} \dot{Q}_{fb} \mathrm{d}t \tag{11}$$

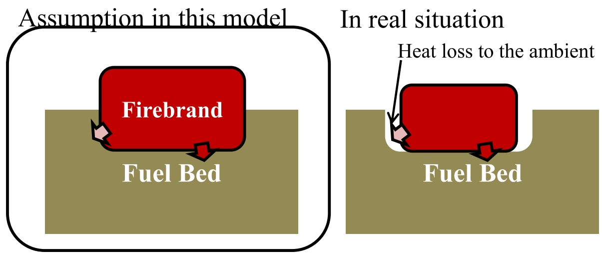

Fig. 4. Assumption in this model on firebrand size. Assuming the size does not change, the surface area of a firebrand remains the same. In addition, heat loss to the ambient (right) (gap between the firebrand and fuel beds due to size change from combustion) is considered to transfer to the fuel beds (left) in this model.

$\dot{Q}_{fb}$ is not constant in this experimental series and is an important factor to have effect on ignition and to be considered here.

Total heat released from a single firebrand, $Q_{comb,1}$, can be described as follows:

$$Q_{comb,\,1} = \Delta H_c \Delta m_{fb,\,1} \tag{12}$$

here, ΔH_c is the heat of combustion of a firebrand and $\Delta m_{fb,1}$ is the mass loss of a single firebrand. This assumption is not considering the shape change over the mass loss for simplicity. With this assumption, the surface area of a firebrand (both $A_{ambient}$ and $A_{embedded}$) can be assumed the same during the period, and the heat loss to the ambient (gap between a firebrand and the fuel beds due to the size change) becomes negligible (see Fig. 4). Assuming the size and the burning rate of firebrands are the same for all firebrands and the number of firebrands (n) is important to ignition:

$$Q_{fb} = \sum_{i=1}^{n} Q_{comb,\,i} \le nQ_{comb,\,1} \tag{13}$$

where $Q_{comb,i}$ is the heat from i *th* firebrand landing on the targeted area of fuel beds. Here $t_{0,i}$ is the time when the i *th* firebrand landing on the targeted area of fuel beds ($t_0 = t_{0,1}$), and $t_{b,i}$ is the time when the i *th* firebrand burning out. Therefore:

$$Q_{comb,\,i} = Q_{comb,\,1} \left(t_{ig} - t_{0,\,i} \ge t_{b,i} - t_{0,\,i}\right) \tag{14}$$

Or

$$Q_{comb,\,i} = f \times \frac{t_{ig} - t_{0,\,i}}{t_{b,i} - t_{0,\,i}} Q_{comb,\,1} \left(t_{ig} - t_{0,\,i} < t_{b,i} - t_{0,\,i}\right) \tag{15}$$

where f is defined as the accumulation factor. In this study, f is still unknown and assumed to be equal to one for simplicity. Eq. (11) does not necessary mean that all firebrands must deposit at the same time. The contribution from some of firebrands which landed close to ignition time may be considered to be less than full contribution as shown. For simplicity, Eq. (14) is assumed to be established as being equal for the rest of calculation (all firebrands which land the targeted area are considered to contribute fully).

Submitting Eqs. (4)–(6), (10) and (14) into Eq. (1) yields and the following:

$$n = \frac{1}{\Delta H_c\ \Delta m_{fb,\,1}} \left\{ \left(t_{ig} - t_0\right) A_{ambient} \left[\in \sigma \left(T_{firebrand}{}^4 - T_\infty{}^4\right) + h_{conv}\left(T_{firebrand} - T_\infty\right)\right] + FMC\ \Delta H_{vap} m_{dry,\,fuel} + \rho_{dry,\,fuel}\ c_{fuel}\ V_{fuel}\left(T_{ig} - T_0\right) \right\} \tag{16}$$

Or

$$t_{ig} - t_0 = \frac{n\Delta H_c \Delta m_{fb,\,1} - FMC\Delta H_{vap} m_{dry,\,fuel} - \rho_{dry,\,fuel}\ c_{fuel}\ V_{fuel}\left(T_{ig} - T_0\right)}{A_{ambient}\left[\in \sigma\left(T_{firebrand}{}^4 - T_\infty{}^4\right) + h_{conv}\left(T_{firebrand} - T_\infty\right)\right]} \tag{17}$$

A summary of parameters and values are provided in Table 1. One challenge is many parameters are still unknown (have never been measured) and many assumptions have to be made. Eqs. (16) and (17) is developed for smoldering ignition, not for flaming ignition.

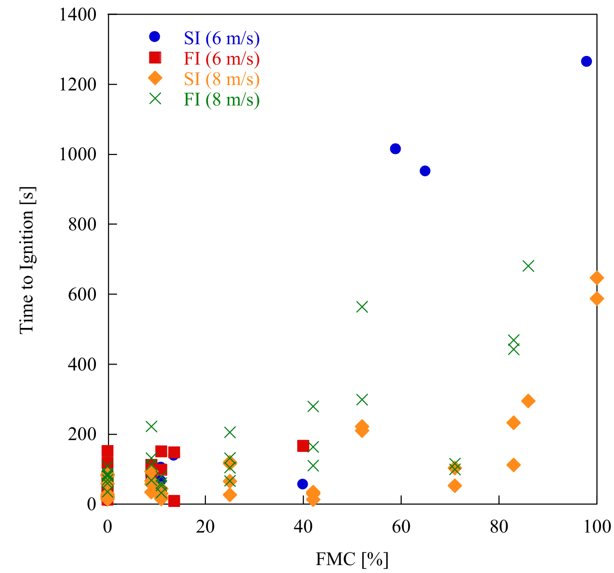

Fig. 5. Time to ignitions and FMC.

4. Results & discussion

Ignitions were observed on the fuel beds. Time to smoldering ignitions (SI) or flaming ignitions (FI) was measured. For this experimental series, SI was defined as intense white smoke from the targeted area as well as glowing ignitions in fuel beds, and FI was defined when *sustained* flaming ignition (more than 1 s) was observed. Many, not all, of SI's were transitioned to FI, depending on wind speeds and FMC. Some of SI's were transitioned to flaming intermittently, not sustained, which was not considered FI. In the case of experiments with 60% FMC under a 6 m/s wind, sustained SI was observed but never transitioned to FI due to the high FMC. In the case of experiments with 40% FMC, SI was transitioned to FI. As also discussed in [19], this study revealed that the upper limit of FMC for SI-to-FI transition would lie between 40% and 60% for the hardwood shredded mulch beds under 6 m/s wind speed. On the other hand, if wind speed increased to 8 m/s from 6 m/s, the upper limit of FMC also changed to 86% FMC. In this case, the temperature of firebrands also increase, thus, firebrands could ignite much higher FMC of mulch beds than 6 m/s.

Fig. 5 shows the relationships of time to ignition (SI and FI) under different wind speeds (6 m/s and 8 m/s respectively) as a function of FMC. It is clear ignition occurred more quickly at higher FMC under 8 m/s wind than 6 m/s wind. Fig. 5 also indicates that time to ignition increases as FMC increases, and there is critical FMC from SI to FI transition under different wind speeds. SI to FI transitions are complicated phenomena [29], involving many parameters. In the case of ignition by firebrands, possible parameters may be wind speed, number of firebrands, fuel bed geometry, and FMC. In this study, FMC and wind speed was changed systematically as these are important parameters in firebrand transport and ignition of wildland and WUI fuels by firebrands. To better represent realistic situations, showers of firebrands were used. SI was observed up to 100% FMC for both wind speeds tested, and FI was observed up to 40% FMC and 86% FMC for 6 m/s and 8 m/s, respectively. This FMC is higher than previous studies on FMC effect on ignitions by a single firebrand [11–17]. It is known that accumulated firebrands can ignite fuel beds which are impossible for a single large firebrand/crib to ignite due to lack of continuous attack of firebrands [18,30]. It is necessary for firebrands to deposit intermittently to heat the fuel beds continuously.

Fig. 6 investigates the effect of FMC on the number of firebrands required for ignition (SI and FI). Higher FMC requires more firebrands to ignite fuel beds and fewer firebrands are required at 8 m/s than 6 m/s,

Table 1
Values and assumptions for parameters.

$\Delta m_{fb,1}$	0.025 g	Observation (half from original state)	
ΔH_c	10 MJ/kg	[24]	
T_{ig}	723 K	[25]	This data is for solid wood, not for shredded hardwood mulch as the data is unavailable
$T_{firebrand}$	1000 K	[26]	2.4 m/s wind speed; No data available to higher wind speed such as 6 m/s and 8 m/s
T_{∞}	293 K	Room temperature	
T_0	293 K	Room temperature	
ΔH_{vap}	2260 kJ/kg	[27]	
$\rho_{dry,fuel}$	0.25 g/cm^3	Measurement (average)	
c_{fuel}	1.112 kJ/kg K	[28]	Pine spruce wood pieces
A_{fb}	2.7 cm^2	Measurement (average)	

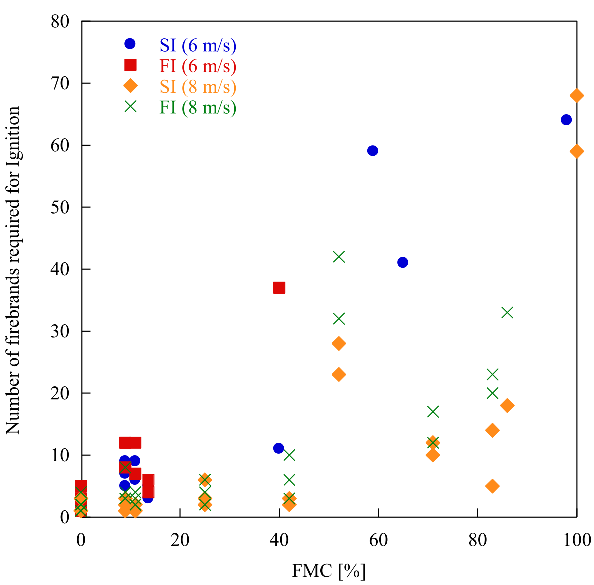

Fig. 6. Number of firebrands required for ignitions and FMC.

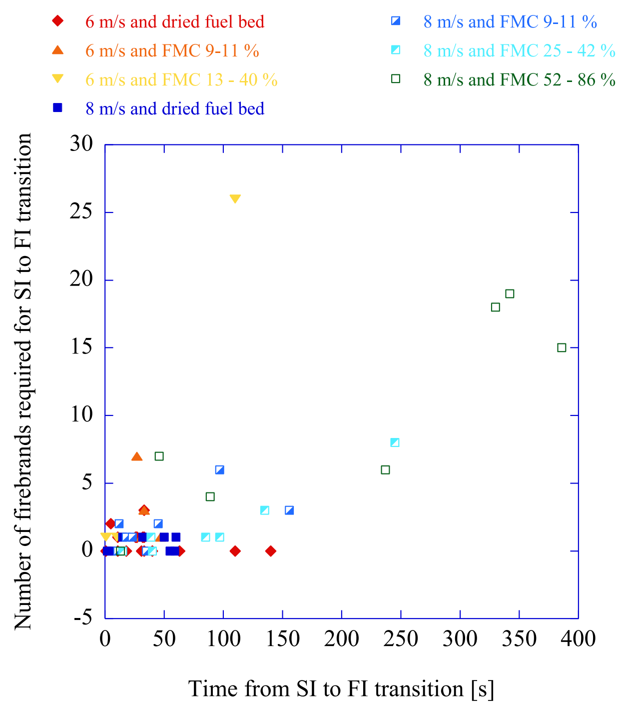

Fig. 7. Time from SI to FI transition and Number of firebrands required for SI to FI transition.

except around 100% FMC (SI). For data for ignition at 50% FMC fuel beds under 8 m/s wind speed, the number of firebrands required for ignition was observed to be larger than at 60% - 90% FMC under 8 m/s. As seen in Fig. 5, time to ignition at 50% FMC fuel beds under 8 m/s wind is also longer than at 60% - 90% FMC fuel beds under 8 m/s. This was due to firebrand accumulation patterns. In this experimental series, firebrand accumulation patterns were controlled only by wind, which is a reason for uncertainties seen in Figs. 5 and 6. With taking consideration into those at 100% FMC, the data at 50% FMC under 8 m/s can be considered within uncertainties. Fig. 6 shows the upper limit of the number of firebrands required for FI, which is around 40 firebrands for both at wind speeds (6 m/s and 8 m/s) regardless of FMC in this study. Forty firebrands correspond to around 2 g mass. The number of firebrands and the ignition time usually correlates, while the number of firebrands defines this upper limit for ignitions. The upper limit of ignition time may exist beyond this experimental condition (more than 100% FMC), and the result implies that the upper limit of ignition time depends on wind speed.

The SI-to-FI-transition phenomenon was closely investigated (shown in Fig. 7). Some of SI simply transitioned to FI without additional heat sources (firebrands); simply with wind and time. For dried fuel beds under 6 m/s wind, one of SI to FI transition took almost 150 s (with no additional firebrands) while most of them were shorter than that. Depending on the firebrand condition and position with the fuel beds, the additional heat from firebrands may contribute to the SI-to-FI-transition phenomena in the fuel beds, which result in quicker transitions. In some cases, even though there is no additional heat contribution from firebrands to smoldering fuel beds, the SI-to-FI-transition were not impossible. The time from SI to FI transition was observed to be longer as FMC increased. At higher FMC, around the upper limit of SI to FI transition, it is shown that more firebrands are required for transition.

When firebrands landed on the fuels, firebrands may stay on the surface of the fuel beds, embed in the fuel beds, or stay somewhere between these two situations. Fig. 8 shows some of the possible placements of firebrands in/on the fuel beds. This depends on the fuel beds and the size of firebrands. If the fuel beds are solid, firebrands stay on the surface. If the fuels are porous such as pine needle or shredded hardwood mulch in the case of this study, how firebrands contact with the fuel beds is dependent on firebrand deposition. As seen in Eqs. (2), (3), (6) and (10), this would have an effect on heat transfer processes between two as $A_{embedded}$ and $A_{ambient}$ change. The combination of shredded hardwood mulch and the size of firebrands in this study made it possible to investigate the variety of the placement of firebrands in/on the fuel beds. Known as the chimney effect, there is a position for firebrands to ignite fuel beds (both SI and FI) easier than others (seen in Fig. 8 (bottom)), which is also indicated in past studies [4,29]. The experimental uncertainties are considered coming from those effects.

Wind effect should be considered in evaporation, convection, and combustion in Eq. (1). The evaporation is known to be less dependent of wind speed with the range of our interest [31]. Convective cooling would be enhanced as the wind speed increases and the heat produced

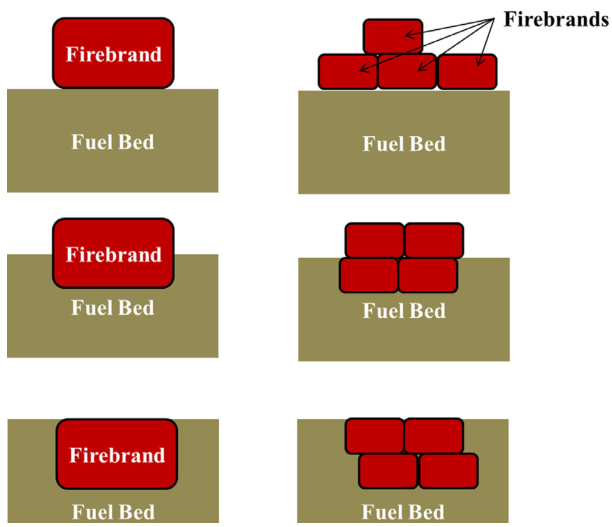

Fig. 8. Examples of firebrand(s) location with fuel beds. Left: Single firebrand, Right: Multiple firebrands, Top: Firebrand(s) on the fuel bed, Middle; Half (or Some) of firebrand(s) buried within fuel bed, Bottom: Entire firebrand(s) within fuel bed. (Not to scale for firebrand size).

from combustion of firebrands is considered to increase as the oxygen provided to firebrand surface increases [32]. In [24], ΔH_{comb} was assumed to be 10 MJ/kg considering firebrands were in the smoldering state and not in the complete combustion of wood. As the wind increased and the air supply increased to the firebrands, the more oxygen was provided to the firebrand at 8 m/s applied wind than at 6 m/s applied wind. The increase in oxygen supply enhances the combustion, which increase the temperature of firebrands and ΔH_{comb} was assumed larger at 8 m/s than 6 m/s in this study based on [32]. In addition, the firebrand mass loss would be larger under the higher wind speed, as shown in [4]. As the heat produced from firebrands depends on both factors, overall heat produced from firebrands is higher at higher wind speed. As the temperature of firebrands increases, radiation heat loss and convection heat loss increases. In addition the convective cooling (the convective heat loss) increases as the wind speed increases. With experimental results [18], the increase in loss is considered to be smaller than the increase of heat produced from combustion of firebrands.

The current heat transfer model does not consider the increase of temperature of firebrands by accumulation nor the temperature gradient within firebrand(s). Some study showed the temperature gradient within a firebrand clearly [26,33], and others did not [34]. This behavior also depends on wind speeds, no study has been undertaken for more realistic wind velocities such as 6 m/s and 8 m/s. For a short duration, the firebrand temperature remained similar [26] or decreased [33]. It is also unknown how this behavior is related to wind speeds, while in [26] a higher wind speed of 2.4 m/s maintained constant temperature longer. A recent study showed that piles of firebrands enhanced heat flux within firebrands, resulting in higher temperature than a single firebrand as well as the temperature gradient within a pile of firebrands [35]. While the condition was different as such applicable data is not quite available for now, this effect might be applicable given the fact several firebrands exist close enough at the same time at some moments during the heating phase. The pile in [35] was quite large compared to the accumulated firebrands for this study. The temperature increase will enhance combustion, which increases the mass loss rate of firebrands and decreases the burnout time. At the same time, convective and radiant heat loss to the ambience will increase. With current firebrand temperature measurement techniques, the temperature increase by a few firebrands is unknown, and it will be a future challenge to be able to measure the temperature increase using advanced thermal measurements yet developed.

5. Summary

The time to the ignition was compared with the ignition behavior, the number of firebrands required for sustained ignition (both smoldering and flaming) was also investigated. The results show that accumulation of firebrands may be the key to ignite high FMC fuel bed. The shredded hardwood mulch used in this study contains a variety of size of hardwood. This is very realistic situation and also leads to interesting findings. In dried conditions, a single firebrand was able to ignite fuel beds, which is the same result from literature [12–18]. With fuel moisture content increased, a single firebrand was not able to ignite; ignition requires more than one firebrand. This can be explained as follows; the fuel bed with given mass was heated continuously by firebrands intermittently depositing and accumulating on the fuel beds. The number of firebrands required for ignition was larger at 6 m/s than that at 8 m/s. A simple model was developed to understand these complex processes. Further efforts to validate this model require high fidelity measurements of important physical parameters needed to better understand firebrand combustion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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