Ignition of cellulose fuel beds by hot metal particles

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Abstract

Spotting occurs in wildland fires when fire-lofted embers or hot particles are carried by the wind and fall in areas of unburnt yet flammable vegetation leading to ignition of new, discrete fires. Significant work has been conducted on predicting the trajectories of the embers but little fundamental work is available related to the capability of these embers or particles to ignite vegetation. This paper consists of an experimental and theoretical study of ignition of fuel beds by hot metal particles. Both laboratory and real life fuel beds have been tested. Spherical steel particles with diameters in the range 0.8 to 19.1 mm heated to temperatures between 500 and 1300ºC are used in the experiments. A relationship between the size of the particle and temperature required for flaming or smoldering ignition is found in powdered cellulose. These results are used to assess a model based on Hot Spot Ignition Theory to determine the particle size-temperature relationship required for ignition of a cellulose fuel bed. The model qualitatively predicts the ignition response of the fuel to a given particle size and temperature. Similar experiments were also conducted using pine needles as the fuel bed.

Keywords: ignition by hot particles, fire spotting.

1 Introduction

Under dry, hot, and windy conditions devastating wildland and wildland urban interface (WUI) fires can be spread by spotting. Spotting leads to more rapid fire spread than flame front propagation because embers generated by burning

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vegetation or structures are lofted by fire plumes and transported downwind to ignite secondary fires or structures remote from the fire front. Spotting fires are especially dangerous on the WUI because this mode of fire spread can surround firefighters as they attempt to fight the fire and civilians and they try to evacuate the area. Many structures destroyed during WUI fires are not ignited by direct flame impingement, but rather by embers penetrating vents/eaves or direct ignition of roof construction and other “soft” targets. Following the devastating 1994 Sydney wildland fires, a statistical study determined that 75% of houses were ignited by firebrands, while 25% were ignited by firebrands and flame radiation (Ramsey and MacArthur [1]). A typical example showing ignition of houses by embers, from the Witch Creek Fire in San Diego, California, is shown in Figure 1 (www.sandiegonewsphotographer.com [2]). Two houses are completely destroyed while the surrounding vegetation is unburned and several surrounding houses remain intact. Molten or burning particles can also be generated by high-voltage powerline conductors clashing in high winds. When these hot particles (typically copper or aluminum) reach the ground they may ignite fires in surrounding dry vegetation.

Figure 1: Aerial photograph taken following the 2007 Witch Creek Fire (www.sandiegonewsphotographer.com [2]). Vegetation unburned, but two houses are completely destroyed while surrounding houses remain intact, suggesting ignition by lofted embers or firebrands.

The ability to accurately predict whether an ember or heated particle having certain characteristics represents a competent ignition source for a given fuel bed has not been thoroughly investigated. Only a few studies have examined the critical conditions that can lead to fire initiation after the landing of a firebrand or particle on a particular fuel bed. These studies are primarily experimental in nature (Stokes [3], Rowntree and Stokes [4], Manzello *et al.* [5–5], Pitts [6]) and no comprehensive theoretical studies have yet been conducted to analyze the problem, or develop generalized predictive tools. Consequently, current models of wildland fire propagation (Finney [7], Linn *et al.* [8], Mell *et al.* [9]) lack capabilities for accurately predicting the initiation of spot fires.

The work presented here is a step toward developing the knowledge needed to accurately predict the conditions leading to ignition of fuel beds by embers and heated particles. Inert steel spheres are used to approximate firebrands/heated particles as this removes uncertainty introduced by the burning ember (ember temperature, char layer thickness, combustion characteristics, thermal properties, etc.). Similarly, powdered cellulose is used as the target fuel because it is homogeneous in composition and has known properties. Additionally, a simplified analytical treatment based on the classical hot spot theory is reviewed and its predictive capabilities are assessed. Finally, to test a 'real world' fuel, a fuel bed of pine needles in order to determine a minimum particle diameter for ignition.

2 Background

2.1 Firebrand/particle generation and transport

Firebrand generation is the process through which natural fuels broken into smaller burning pieces during a fire and lofted by a buoyant fire-induced plume or powerlines interact generating molten metal particles. Yoshioka *et al.* [10] and Manzello *et al.* [5, 11] have characterized the number and size distribution of brands generated by different fuels. Firebrands generated by a single Douglas fir can range in size from 200 mm to around 10 mm in diameter.

The trajectories and burning rates of firebrands or heated particles lofted by fires have been studied more extensively (Tarifa *et al.* [14], Koo *et al.* [23]. Collectively, the above studies show that small embers or particles are easily lofted and can travel long distances. However, they may burn out or have a low temperature at landing. In comparison, large embers or particles may have long burn times, but they are more difficult to transport and therefore do not travel far from the fire front. Embers or particles of intermediate size have a relatively long burn time and can be lofted considerable distances.

2.2 Spot fire formation

The aspect of spot fire formation that is least understood is what happens after a firebrand or heated particle lands on a target fuel bed. Of greatest interest is whether or not ignition occurs. This complex process depends on several factors, including the size and state of the brand (temperature, smoldering/glowing, flaming), the characteristics of the fuel bed on which it lands (temperature, density, porosity, moisture content), and environmental conditions (temperature, humidity, wind velocity). Ignition of fuel beds by fire brands and heated surfaces has been studied primarily experimentally, in particular by workers at NIST [4–7]. Studies on the ignition by metal particles have been reported by Rowntree and Stokes [3, 4].

Using single glowing embers of Douglas Fir (5 or 10 mm diameter, 51 and 76 mm length respectively) under air flow of 0.5 or 1 m/s, Manzello *et al.* [5] found that smoldering ignition would occur in shredded paper but no ignition would occur in pine needles or hardwoods. For flaming embers under the same conditions, flaming ignition would occur in all fuels except hardwood mulch at

11% moisture content. Similar results are found using disk shaped embers Manzello *et al*. [5, 6] where flaming ignition occurred only when flaming embers are dropped.

A few theoretical studies related to ignition of fuel beds by have been conducted, but these models remain largely unvalidated. In particular, “hot spot” theories as originally developed in the 1960s and 1970s (Gol’dshleger *et al*. [24], Thomas [28] and applied later Jones [29–31] to natural fuels seem to be the most promising simple approach. More recently, detailed numerical models have been applied to simulate spot fire initiation (Zvyagils’kaya and Subbotin [32], Lautenberger and Fernandez-Pello [34].

Babrauskas [33] discusses the possibility of using energy as a criterion for ignition and concludes that it is not sufficient as particles of different size with the same energy do not necessarily result in ignition. He also notes that laboratory studies to date do not allow the determination of which thermal properties dictate incendivity. Babrauskas concludes that a “hot spot” ignition theory will allow reasonable prediction of particle size-temperature relationships for ignition.

3 Experiment description

The experimental apparatus used in this work is shown in Figure 2. The fuel bed is mounted in the bottom of a wind tunnel with the sample surface flush with bottom of the tunnel. The wind-tunnel is 550 mm in length with a 130 mm by 80 mm cross section. The sample holder is 150 mm long, 100 mm wide and 50 mm deep and its leading edge is 150 mm from the inlet of the tunnel. The fuel was dry powdered α-cellulose (bulk density of approximately 200 kg·m^3). The mass and volume of the cellulose remained constant throughout the tests. A similar procedure was used to condition the pine needles fuel bed. Compressed air flows through the tunnel at a velocity of 0.5 m/s. Sheathed K-type thermocouples are placed in the fuel sample at locations shown in Figure 3. The thermocouples are used to follow the progress of the smolder or flame front

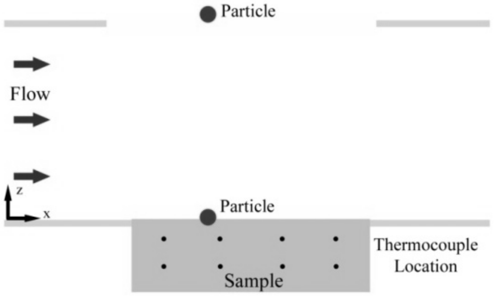

Figure 2: Simplified schematic.

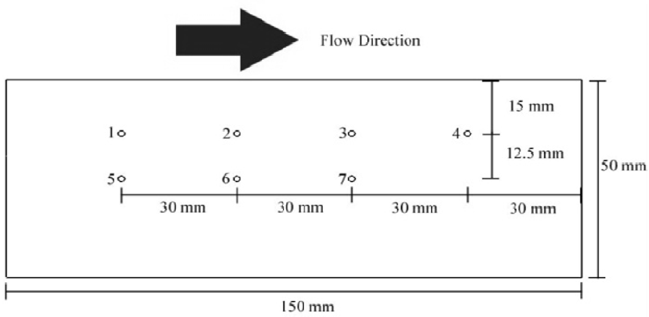

Figure 3: Fuel bed dimensions and thermocouple locations.

through the fuel bed. Spherical steel particles with a diameter between 0.8 and 19.1 mm heated to temperatures between 500 and 1300ºC were used to simulate the embers or heated particles.

During an experiment, a steel particle of desired size is heated with a propane or propylene torch. Once the particle has reached the desired temperature it is dropped onto the sample surface from a height of approximately 20 mm. The particle is dropped approximately 35 mm from the leading edge of the sample. Fuel bed temperature is recorded along the centerline at seven locations as shown in Figure 3.

4 Experimental results

4.1 Powdered cellulose results

Experiments are undertaken to identify the relationship between hot particle size and temperature and the ignition in a sample of cellulose. The powdered cellulose was observed to undergo both flaming and smoldering ignition depending on the particle characteristics. In flaming ignition the flame would be initiated around the hot particle and if the particle was hot enough, flames would propagate across the free surface of the fuel sample then extinguish as they reach the sample's end. In depth smoldering would then be seen to continue for several hours.

In the case of smoldering ignition, a smolder front would be established around the hot particle. This would then propagate laterally as well as in depth. In all cases when smoldering was ignited, the sample was seen to burn to completion. Transition from smoldering to flaming was not observed.

4.1.1 Temperature profiles

Figure 4 shows the temperature profile for a sample in which flaming occurred initially across the surface of the sample followed by in depth smoldering. Peak fuel bed temperatures are in the range 465°C to 550°C. Temperatures in depth were higher than those closer to the free surface due to reduced heat losses. The

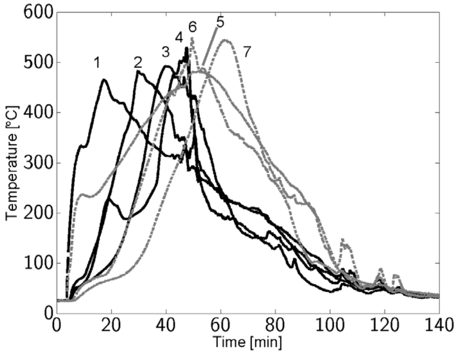

Figure 4: Temperature profiles in the fuel bed for a sample in which flaming was observed. Thermocouple locations refer to those in Figure 3.

temperature peak in the solid phase advances both laterally and in depth from the point where the hot particle was dropped.

4.1.2 Smolder spread rate

The smolder spread rate was found to be a function of depth and distance from the hot particle. Spread rate was calculated by finding the times each thermocouple reached 300°C and dividing the distance between the thermocouples by the time between adjacent thermocouples reaching this temperature.

For the example above, at a depth of 15 mm below the free surface, spread rates were 2.0, 3.1 and 5.3 mm/min at positions between 30 and 60, 60 and 90 and 90 and 120 mm from the leading edge respectively. This suggests that as the size of the reaction front grows, the spread rate increases. However, at a depth of 17.5 mm below the free surface, this effect is much reduced and the spread rates are 2.9 and 2.7 mm/min at between thermocouple locations 30 and 60 mm and 60 and 90 mm from the leading edge respectively. These spread rates are in agreement with others reported in the literature (Rein [36]).

4.1.3 Propensity for ignition

Figure 5 shows the ignition propensity as a function of particle size and temperature. Triangles represent direct flaming ignition, squares are smoldering ignition, and asterisks represent no ignition. The data clearly show a demarcation between no ignition, smoldering ignition and flaming ignition and that both for flaming and smolder ignition smaller particles require higher temperatures than larger particles. Due to the experimental method for delivering the hot particles, it was not always possible to ensure the particles were exactly the same temperature upon landing on the fuel and obtained the same level of submergence in the cellulose. The result is that there is some overlap between the ignition types in some cases

For the range of particles tested, the minimum particle temperature at which smoldering could be ignited was 550°C and the minimum temperature at

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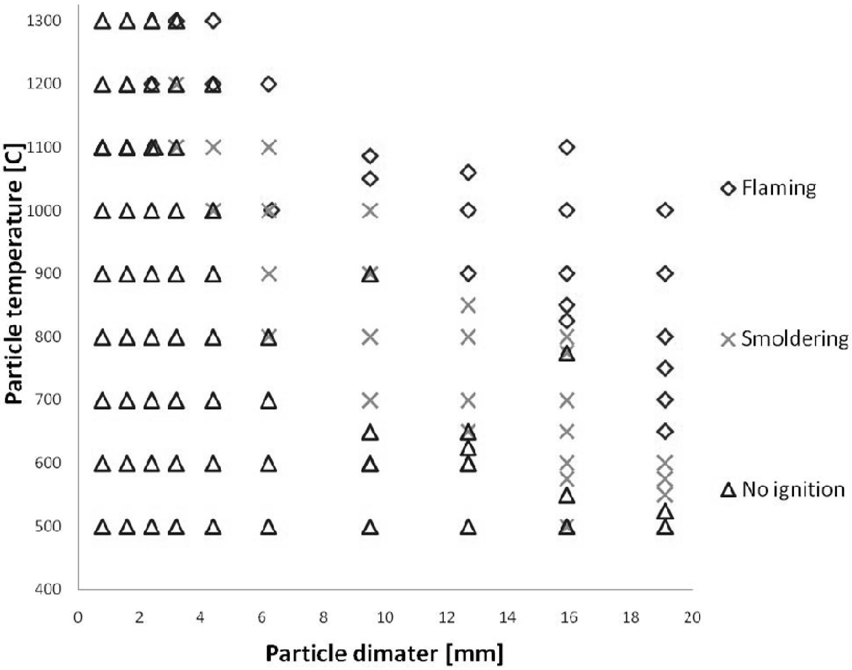

Figure 5: Ignition propensity of dry cellulose using heated steel spheres.

which flaming ignition occurred was 650°C. In both cases, this was for a particle diameter of 19.1 mm. Flaming was observed for particles larger than 2.4 mm heated to at least 1200°C.

4.1.4 Hot spot theory

It has been suggested that hot spot theory (Gol'dshleger *et al.* [24], Thomas [28]) can be used to model the ignition of natural fuels by heated particles. For example, in a sequence of three papers, Jones [29–31] applied hot spot theory to simulate the ignition of forest litter by copper particles. In Jones [29], the theory of Gol'dshleger *et al.* [22] is applied. This same theory (Gol'dshleger *et al.* [24]) has been recommended by Bowes [35] for its compromise between accuracy and tractability, and has also been applied by Babrauskas [33] to model the barley grass ignition experiments of Rowntree and Stokes [4] involving heated particles. Since the hot spot theory of Gol'dshleger *et al.* [22] seems a logical starting point for modeling the present experiments, it is developed in detail in Hadden *et al.* [38] then applied to correlate the present experiments. The governing equation for hot spot theory is show in eqn (1).

$$r_{cr} = \delta_{cr}\sqrt{\frac{k}{\rho A \Delta H}\frac{RT_{p0}^2}{E}\exp\left(\frac{E}{RT_{p_0}}\right)} \tag{1}$$

The constants in eqn (1) can be determined experimentally. By creating two constants, C_1 and C_2, defined as follows:

$$C_1 = \delta_{cr}\sqrt{\frac{k}{\rho A \Delta H}\frac{RT_{p0}^2}{E}} \tag{2}$$

$$C_2 = \frac{E}{R} \tag{3}$$

by making these substitutions eqn (1) becomes the following:

$$2r_p = C_1 T_p \sqrt{\left(\exp\left(\frac{C_2}{T_p}\right)\right)} \tag{4}$$

The regions of flaming, smoldering and no ignition can be demarcated by using a curve fit to find C_1 and C_2. The values of C_1 and C_2 for smoldering and flaming ignition are given in Table 1.

Table 1: Values of constants for demarcation of ignition regimes.

	C_1	C_2
Smoldering	0.00034	4912
Flaming	0.00054	5452

The results of Figure 6 agree qualitatively with those of Stokes and Rowntree [3, 4]. An interesting feature of Figure 6 is the narrowing of the smolder region, suggesting that particles above a certain longer cause smoldering ignition to occur in the fuel. Further testing is required to identify the exact temperature at which this occurs.

4.2 Pine needles results

Ember ignition of pine needles has been studied as a function of the size of the hot particles. Particles of sizes 18, 15, 12, 10, 7 and 5 mm have been studied. In all cases, particles were heated to approximately 1100°C using a propane torch. A wind speed of 0.54 m/s was used. The bulk density of the pine needle bed was 25 kg/m^3.

In order to determine the risk associated with embers of various sizes, a criterion needs to be chosen to determine the extent of combustion. In this work, mass loss is used. Figure 7 shows mass loss as a function of ember size. Unsustained smolder results in localized mass loss in the region of the ember around 2–5%. If the sample transitions to flaming or flames from the outset then mass loss is high 85–91%. No samples were observed to smolder to any great extent without the transition to flaming occurring. It is seen that for the present tests the minimum particle size for flaming ignition is around 8 mm.

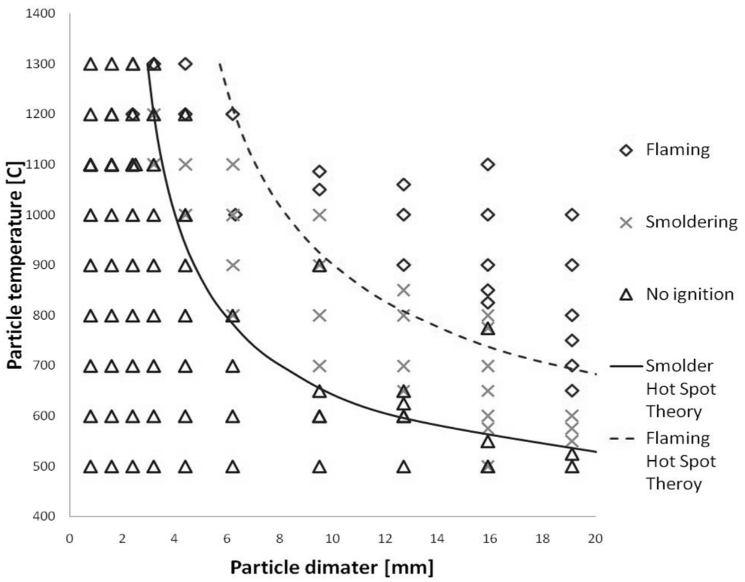

Figure 6: Ignition propensity of dry cellulose using heated steel spheres correlated using hot spot theory.

Figure 7 also highlights one of the difficulties with the experiments using real fuels: ensuring consistency in ember position and depth in the fuel sample. This depends on the structure of the fuel bed as the pine needles are inhomogeneous. This can result in samples not igniting consistently such as those using a 15 mm particle in Figure 7. This means that a probabilistic approach is required to study the problem and good characterization of the fuel bed is important.

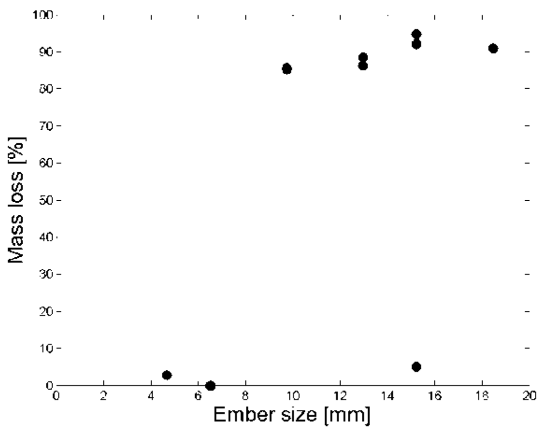

Figure 7: Mass loss of sample as a function of particle size. Wind speed was constant at 0.5 m/s.

5 Concluding remarks

Ignition of cellulose fuel beds by hot spherical particles has been studied experimentally and a model of hot spot ignition presented. The results show as particle size is reduced; increased temperature is required for ignition. For a particle size of 2.4 mm, temperatures of 1200°C were required for flaming ignition and this was reduced to 650ºC for particles of 19.1 mm. This suggests that the ignition propensity is a function of both particle size and particle temperature. Additionally, hot spot ignition theory seems to provide qualitative agreement with experimental results and with continued development may allow good correlation.

Experiments using a real fuel to determine the likelihood of ignition of a bed of pine needles as a function of hot particle size have been undertaken. It is suggested that there is a minimum particle size of 8mm in order for the pine needles to transition to flaming. Due to the inhomogenous nature of pine needles, the ability to predict the behavior of such fuels is vital in improving wild fire spread models and results will be used to improve and validate the model using such materials. In the future, more experiments involving variations in windspeed, particle/ember type, and fuel bed type will help in the creation of a model to improve prediction and encapsulate the transition to flame. This will be an aid in the creation of fire danger maps on the urban/wildland interface.

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