Ignition Behavior of Powdered Cellulose by Hot Steel Spheres

James L. Urban    Casey D. Zak    Carlos Fernandez-Pello

Mechanical Engineering Department,
University of California Berkeley, Berkeley, CA 94720-1740

The flaming ignition behavior of powdered cellulose fuel beds by hot steel spheres of various diameters (2.38 to 15.9 mm) and initial temperatures (625°C to 1100°C) was studied using high speed schlieren videography. Understanding ignition in this scenario could offer insight into the mechanisms by which metal particles initiate wildland and Wildland Urban Interface (WUI) spotting fires. Earlier work on this topic has shown that ignition propensity has a relationship with the temperature and diameter of the sphere. However, little is known about the physical processes governing this relationship. This work provides further information regarding the conditions required for ignition, and useful observations for the development of a theoretical framework for predicting ignition propensity of combustible fuel beds. For the conditions tested, powdered cellulose ignition appears to exhibit limiting behavior in two regimes: sphere temperatures below 650°C did not ignite the cellulose and spheres with diameters below 3.18 mm and temperatures up to 1100°C did not ignite the cellulose either. The experiments suggest that the ignition time is considerably shorter (88 ms on average) in tests using spheres with diameters greater than 7 mm, while those with diameters less than 7 mm take considerably longer (262 ms on average) to ignite. Furthermore, qualitative analysis of high speed schlieren videos shows differences in pyrolysis and ignition behavior and suggests that, in these limiting regimes, there are different processes controlling ignition and that the particle requirements for ignition may be different.

1 Introduction

According to the National Fire Protection Association of the United States, wildland fires caused more than 600 million dollars in property damage and killed 65 civilians in the year 2011 [1]. These fires are also responsible for significant biomass consumption and are a large source of combustion emissions to the atmosphere [2,3]. Clearly, wildland and Wildland Urban Interface (WUI) fires have caused significant environmental and property damage, as well as the loss of life. Some of these fires allegedly begin when hot metallic particles land in combustible fuel beds, such as duff, litter or sawdust. These particles can be the result of powerline interactions, grinding or other industrial activities. Currently, the exact process by which this ignition occurs and the conditions necessary to initiate a spot fire are not well understood. Consequently, current wildland fire models lack capabilities for accurately predicting the initiation of spot fires [4,5]. A greater understanding of this ignition process and the conditions necessary for ignition could lead to improved predictive models and reduced losses due to fire.

There are only a few studies published on the ignition of fuel beds by hot metal particles [6-10]. The present work complements previous works and attempts to provide a better understanding of the problem. Our approach has been to conduct similar experiments, but using a more idealized scenario, specifically, focusing on the ignition of powdered cellulose fuel beds by hot stainless...
steel spheres. This simplified laboratory case allows us to more easily examine the fundamental controlling parameters and underlying mechanisms at work in real world ignition scenarios. We utilized high-speed video and radial schlieren imaging to investigate ignition behavior over a range of sphere diameters and temperatures. Schlieren techniques allowed us to observe pyrolyzate dynamics shortly before and during ignition, as well as more accurately identify the ignition time and location. In the following sections, we briefly describe our experimental method and then discuss the observed ignition phenomena and behavior along with corresponding ignition times.

2 Experimental Design

For these tests stainless steel spheres of Alloy 302 were heated in a tube furnace and then dropped into a powdered cellulose fuel bed inside a bench-scale wind tunnel. The spheres varied in size between 2.38 mm to 15.88 mm with initial temperatures in the range of 625°C to 1100°C. The fuel bed was composed of α-cellulose \( (C_6H_{10}O_5)_n \). Cellulose was chosen as it is a primary constituent of most natural fuels and unlike natural fuels cellulose is chemically homogeneous and has better defined properties than natural fuels. For all tests the settled volume was held constant. The settled volume is the minimum volume occupied by the powdered solid fuel after vigorous manual shaking. The bulk density of the fuel varied between 239 to 341 kg/m\(^3\), approximately the value listed by the manufacturer. During experiments the moisture content was not controlled. The cellulose was open to laboratory conditions and the ambient laboratory temperature and the moisture content for each fuel bed were recorded before each experiment. The average moisture content of the tests was 6.28±0.41% with an average temperature of 23.5±0.6°C.

An isometric sketch of the experimental apparatus is shown in Figure 1a as well as a photograph in Figure 2. The fuel bed is flush with the bottom of the wind tunnel that has a cross section of 80 mm in height, 100 mm in width and the fuel bed is 150 mm long. House Air is flown through the tunnel at .5m/s. The particles are heated in an electrical tube furnace by inserting them into the oven with a ceramic spoon that is held by a linear guide 140 mm above the fuel bed. The linear guide allows the spoon to be inserted and removed from the tube furnace so that the spheres can be
dropped onto the fuel bed. The sides of the wind tunnel test section are glass windows which allow optical access for highspeed schlieren videography. Shown in Figure 1b is a double-pass schlieren configuration with a 1 m focal length spherical mirror and a radial rainbow ‘bullseye’ filter. The schlieren video was recorded at 1200 frames per second using a digital camera. Inside the wind tunnel the velocity at the centerline of the flow varied from .5 m/s to .3 m/s across the length of the fuel bed.

![Figure 2: Photograph of experimental set-up](image)

Each experiment consisted of placing a sphere on the ceramic spoon and then inserting the spoon with the ball into the tube furnace so that it could reach thermal equilibrium with the furnace. Once at equilibrium, the spoon was removed from the furnace along the linear guide and then rapidly turned, dropping the ball onto the fuel bed. Approximately $610 \pm 170$ ms elapsed between the moment the sphere exits the tube furnace and the moment it impacts the fuel bed. Tests were either reported as ”no ignition” or ”flaming ignition”. Experiments with thermal degradation of the cellulose or charring were considered ”no ignition” for the purposes of this study because even if smolder was initiated it was not possible to determine if transition from smolder to flaming could occur. Flaming ignition was defined as the presence of a visible flame that lasted for more than 1 second. For each experiment with flaming ignition the ignition delay time was recorded. A minimum of five experiments were conducted for each pair of sphere diameter and temperature.

3 Results and Discussion

The results of the ignition tests are shown in Figure 3. The circles on the plot are colored according to their observed probability of ignition following the color legend on the right of the plot. The probability of ignition was defined as the number of flaming ignition occurrences divided by the total number of tests conducted for a given set of conditions.

We expect the ignition results to vary binomially since each test results in either ignition or no-ignition. To more clearly represent the results we performed a logistic regression on the data using
the EUREQA formalize software package [11]. EUREQA uses machine-learning algorithms to find the best fit between a given data set and large number of possible functional forms. The black trend curve in the figure represents a 50% ignition probability. This line is given by the equation:

\[ 971.218 d_s^2 + 3280.93d_sT_s^2 - 23290.7 = 0, \]  

(1)

where \( d_s \) is the diameter of the sphere and \( T_s \) is the initial temperature of the sphere. Further testing and analysis is required to replace this curve with one based on physical phenomena, but this trend curve is useful for visualizing the ignition behavior. Accordingly, the data agrees qualitatively well with previous studies in that the smaller diameter spheres require higher temperatures to cause ignition. It also indicates asymptotic behavior at low temperatures and small diameters. Ignition was not observed at temperatures below 625°C, despite many tests being performed at that temperature. Similarly, spheres with a diameter of 2.38 mm never ignited at the temperatures studied. Further work is required to determine if spheres of this size will ignite at temperatures up to 1100°C. Following completion of experiments, high-speed video of each of the experiments was analyzed. A sequence of still frames from two ignition events are shown below in Figure 4. Figure 4a depicts the ignition by a 15.9 mm sphere at 650°C and Figure 4b depicts ignition by a 3.18 mm sphere heated to 950°C. The small red circle that appears near the upper left hand corner of all frames is an artifact of the Schlieren imaging technique and is not involved with the ignition process.

There is a general sequence of events common to all recorded tests. First the sphere and its schlieren contrail are seen impacting the fuel bed (frames i, Figure 4). The majority of spheres then bounce and may spin. Upon impact, a Schlieren contour expands away from the sphere indicating the expansion or growth of a hot gas volume. Initially this may be hot air being pushed out of the way by the impinging sphere, but a continued presence indicates the production of gaseous pyrolyzate generated as the sphere heats the surface of the fuel bed. There may also be a pre-

**Figure 3:** Ignition probability as a function of sphere diameter and temperature
Figure 4: Still frames of ignition sequence for a small diameters and high temperature sphere and a large diameter high temperature sphere

ignition exothermic reaction occurring in the area as well. Ignition was observed as early as when the sphere began to bounce away from the fuel bed after the initial impact and as late as after the sphere had come to rest in the fuel bed after one or two bounces on the fuel bed.

When ignition did occur, it is observed as a rapid expansion of the existing hot gas plume, or as a second contour that nucleates within the first (frame v, Figure 4). After the flame front is initiated, it grows in size and eventually anchors to the fuel bed, transitioning to a diffusion flame. The rapid expansion of ignition is clearly illustrated in the differences between frames iv and v in Figure 4b which were taken less than 1 ms apart. The intensity of the schlieren perturbation also increases, to the point that red is observed indicating a very sharp density gradient (frames iv-vi, Figure 4a). When a second contour is observed, its location can vary greatly; ignition occurred on both the bottom and top surfaces of spheres during bouncing, as well as up to 10 mm away from the sphere within the hot gas volume.

In the cases of non-ignition, a dark plume is observed emanating from the sphere and surrounding
fuel bed at some time after the initial impact. A dark appearance in a schlieren image means an object is opaque, suggesting either cellulose particles lofted by the sphere’s impact or heavier products of pyrolysis. These plumes do not appear to behave like lofted particles, but the current resolution of the videos (0.22 mm) is not sufficient to rule out this possibility. Assuming the cloud is some sort of fluid, it seems likely that the opacity is due to a combination of condensed and gaseous pyrolysis products.

We recorded ignition times for the majority of events, and the average times for each diameter and temperature combination are displayed in Figure 5. Here, ignition time is defined as the time between when a sphere first contacts the fuel bed and the first sign of ignition. The recorded values of the ignition delay time ranged from 34 to 673 ms. These ignition time results were then compared to the heat diffusion time of the sphere. The results of this are shown in Figure 6.

![Graph showing the relationship between sphere temperature and ignition time](image)

**Figure 5:** Average ignition time

As indicated by the error bar in Figure 5, there is a great amount of variability in the recorded ignition times. The data suggest two interesting trends. First, it appears that ignition time tends to decrease with increasing temperature for a given sphere diameter. Second, when comparing ignition times near a sphere’s ignition limit, smaller spheres \((d_s \leq 6.35 \text{ mm})\) seem to generally have longer ignition times. These trends may be affected by the sphere’s trajectory after impact and further examination will be required to see how the sphere’s trajectory impacts the propensity of ignition and the ignition delay time. Moreover, the smaller, higher temperature spheres may also transfer energy to the fuel bed in a different way, and this may affect the ignition process. Figure 6 shows that the ignition times of the larger diameter spheres \((d_s \geq 7.94 \text{ mm})\) tend to be directly proportional to the heat diffusion time of the spheres. These observations appear to indicate that the mechanism of cellulose ignition and particle requirement for ignition may be different for large
spheres than for smaller ones. Large spheres may simply need to have a minimum temperature to ignite the cellulose while small spheres may need to have a minimum energy to occur.

![Graph of Sphere Temperature vs. Ignition Time](image)

Figure 6: Ratio of ignition time to heat diffusion time

In addition to the differences between large and small spheres suggested by Figure 5 and Figure 6, other qualitative differences are apparent in the high-speed videos. The larger spheres had a greater propensity to have clumps of cellulose attached to them after impact and produce dark pyrolyzate plumes, even for cases where ignition occurred (see Figure 4a, frames iii-v). In the case of the smaller diameter spheres, wisps of dark pyrolyzate were only occasionally observed and generally the pyrolyzate was only indicated by the schlieren contour. Brief combustion events were also noticed for several small spheres near their apex, as discussed in previous work by our laboratory. These 'flashes' did not result in a stable flame and not counted as 'flaming ignition'.

4 Conclusion

Ignition tests of a cellulose fuel bed have been performed with stainless steel spheres over a range of sphere temperatures and diameters, and the boundaries of ignition have been determined. High-speed schlieren imaging was used to observe and describe the ignition process. Many aspects of the observed behavior are the result of the chosen fuel bed and as a result, the applicability of this work may be restricted to powdered fuels. Ignition propensity appears to behave asymptotically at small diameters and low temperatures (particularly the latter). The differences in qualitative behavior and average ignition times between these two asymptotic regions suggest that there may be different dominant controlling mechanisms and requirements in each of the two limits. Future work in this
area will be focused on identifying these mechanisms and refining the ignition propensity and ignition time data presented above. Many aspects of the observed behavior are the result of the chosen fuel bed and as a result the applicability of this work may be restricted to powdered fuels.

Acknowledgments

We would like to thank Daniel Wagman for help in designing and manufacturing several of the crucial components for our experimental set up, as well as Vi Tran for her help in conducting preliminary tests and assisting in setting up parts of the experimental set-up. Also we would like to thank all of the other graduate students in the Combustion and Fire Processes Laboratory for providing insight and enlightening discussion on many aspects of the experiments. In particular we would like to thank Daniel Murphy who we thank tremendously for helping us implement the imaging techniques in this paper. This research was supported by a National Science Foundation Graduate Research Fellowship and National Science Foundation Award No. CBET-1066520.

References