Understanding ignition of natural fuels by heated particles

C. D. Zak, D. C. Murphy & A. C. Fernandez-Pello
Department of Mechanical Engineering, University of California, USA

Abstract

Wildland and wildland urban interface (WUI) fires pose a serious threat to property, public safety and the environment. Many of these fires are allegedly ignited by heated particles generated by power line interactions, welding and other sources of hot particles. Even so, there has been relatively little research on the ignition of fuel beds by hot particles. This work presents an experimental study of ignition of powdered cellulose fuel beds by hot metal particles. Stainless steel and brass spheres with diameters in the range from 1.59 mm to 12.7 mm were heated to temperatures between 773 and 1373K and dropped onto cellulose fuel beds with moisture contents of 1.5% and 4.5%. The effects of varying particle diameter, temperature and thermal conductivity and fuel bed moisture content on flaming ignition propensity are discussed. The results of this work suggest that ignition of fuel beds by hot particles most strongly depends on particle size and temperature, with a possible dependence on fuel bed moisture content.
Keywords: ignition, hot metallic particle, fuel bed moisture content, thermal conductivity, powdered fuel bed.

1 Introduction

According to the National Fire Protection Association of the United States [1], "outside and other" fires caused more than $500 million dollars in property damage and killed 55 civilians in the year 2010 alone. These fires are also responsible for significant biomass consumption and a large source of combustion emissions to the atmosphere [2, 3]. Clearly, wildland and wildland urban interface (WUI) fires have caused severe environmental and property damage, as well as the loss of life. Many of these fires are allegedly ignited by

WIT Transactions on The Built Environment, Vol 134,
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/SAFE130541

heated particles generated by power line interactions, hot work/welding, overheated catalytic converters, seized train brakes, and other sources of hot particles. 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 the 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 natural fuels by hot metal particles. These studies focused on specific fuels and provided boundaries of ignition and no ignition in terms of particle size and temperature [6–8]. Additionally, Tanaka [9] investigated the effects of fuel bed moisture content on the ignition propensity of steel spheres dropped onto beds of sawdust, but his experimental method was found to be inaccurate. In the work presented here we investigated the effects of varying fuel bed moisture content and particle thermal conductivity as well as particle size and temperature in a controlled laboratory setting.

2 Experimental description

In the investigation to determine necessary conditions for ignition, metallic spheres were heated using a tube furnace and dropped onto a fuel bed seated inside a bench scale wind tunnel. Stainless steel (alloy 302) and brass (alloy 260) spheres were tested to determine the effect of particle thermal conductivity. We assessed the impact of fuel bed moisture content by varying the conditioning of the fuel (see following section). The diameter and temperature of the spheres were varied between 1.59 mm and 12.7 mm and 773K and 1373K respectively. In the case of the brass spheres, heating to 1373K allowed gravity to overcome the surface tension of the particle's outer oxide layer. The particles lost their spherical shape and became a molten pool, making deposition onto the fuel bed very difficult. As a result, no experiments were conducted with brass at 1373K.

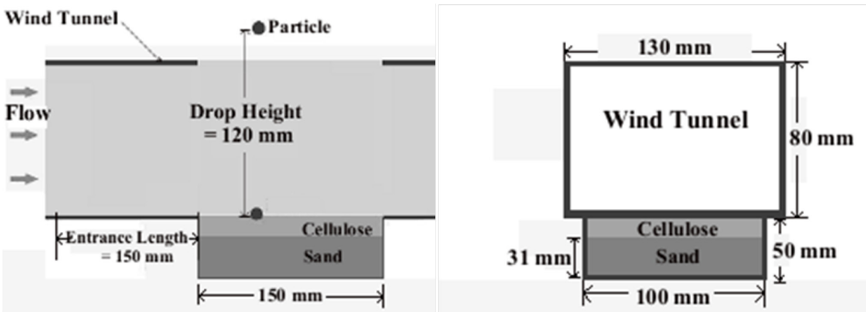
2.1 Fuel bed preparation

The fuel beds were composed of powdered α-cellulose ($C_6H_{10}O_5$). Cellulose is an ideal laboratory fuel because of its chemical homogeneity and the availability of property data. It is also the largest component of woody biomass, making it a reasonable surrogate for more complex fuels. The cellulose used in this work was either laboratory-conditioned or held in a conditioning chamber containing desiccants. For each daily series of experiments, we used approximately 68 grams of cellulose from one of the two sources, resulting in a bulk fuel density of ~239 kg/m^3. An additional sample of 13 grams or more was taken from the same source and used to measure moisture content. The measuring process involved weighing the sample before and after drying in an oven at 383K for 3 hours.

www.witpress.com, ISSN 1743-3509 (on-line)

2.2 Experimental apparatus

The apparatus used in this work is shown in figure 1. Compressed laboratory air was introduced into the tunnel with a centreline velocity of 0.5 m/s. Although based on Reynolds number the flow appears to lie within the transition regime between laminar and turbulent, anemometer measurements made within the tunnel showed the flow to be approximately fully developed and time invariant across the length of the fuel bed. The temperature of the air varied little from day to day and was approximately 297K. Over the course of experiments the relative humidity varied between 6.9% and 12.9% with an average of 9.2%.



(a) (b)

Figure 1: Dimensioned schematic of the experimental apparatus in (a) side view and (b) down tunnel view.

2.3 Experimental procedure

During each run, we inserted a stainless steel or brass sphere into the tube furnace and positioned it in the center of the tube. Once the sphere reached equilibrium with the furnace, the lid of the tunnel was removed and the furnace was tilted. The sphere then rolled down the process tube and dropped into the fuel bed from a height of approximately 120 mm, fig. 1. We then replaced the lid of the tunnel and observed what happened. No effort was made to control penetration depth or local density, but the drop location was varied to randomize any contributing factors associated with the fuel bed. Results were recorded as flaming ignition or no flaming ignition. We defined flaming ignition as the appearance of a visible flame after the particle contacted the bed. Whether the flame later extinguished or transitioned to smoldering was not recorded because any such event was considered to be separate from the ignition phenomenon. Only parameter combinations near the flaming/non-ignition limit were investigated to reduce the number of tests. At least five experiments were performed for any combination of parameters for which ignition seemed possible.

3 Results

3.1 Effect of particle diameter and temperature

Figure 2 shows ignition results as a function of particle diameter and temperature for stainless steel particles at both moisture contents. Figure 3 presents the same data for brass spheres. Triangles indicate parameter combinations that resulted in flaming ignition (FI) for every trial conducted. Circles represent possible flaming ignition (PFI), combinations for which flaming ignition was observed in at least one trial. Diamonds denote no flaming ignition (NFI), cases for which only smoldering or no ignition were observed.

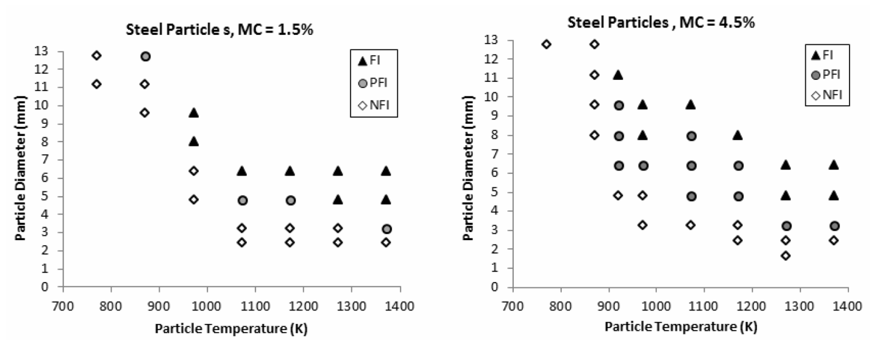


Figure 2: Ignition results for steel particles as a function of size and temperature.

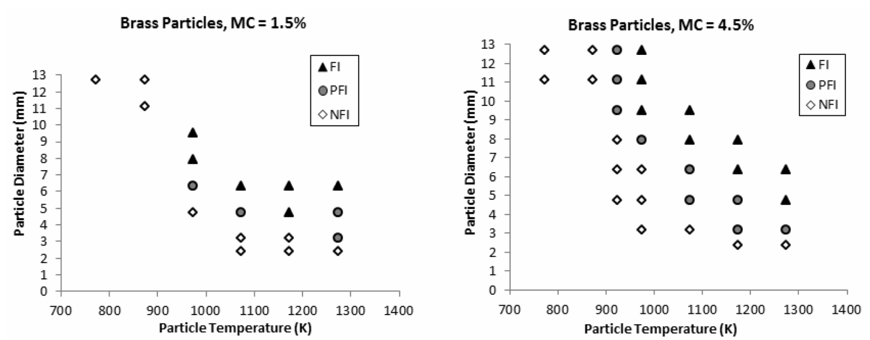


Figure 3: Ignition results for brass particles as a function of size and temperature.

www.witpress.com, ISSN 1743-3509 (on-line)

It is clear in all four plots that small spheres require higher temperatures to ignite than large spheres. The slightly convex nature of the data relative to the origin indicates that at low temperatures ignition is less dependent on diameter than at high temperatures. These trends agree qualitatively with the results of previous investigations [6, 8]. It is interesting to note that the melting range for brass is 1188-1228K. Figure 3 does not show a clear change in the ignition behavior of brass particles as a result of melting, even though it would be expected that the enthalpy of melting would contribute to the energy transferred to the fuel bed.

In the size and temperature ranges under study, flaming ignition never occurred at temperatures less than 873K, and consistent flaming was only observed for temperatures of 923K or greater. Based on the general trend of the data, this may represent a temperature asymptote somewhere near 873K. Similarly, ignition was never observed for particles smaller than 3.18 mm and consistent flaming required diameters of 4.76 mm or greater. This also indicates that an ignition asymptote associated with the diameter may exist.

3.2 Effect of fuel bed moisture content

Fuel bed moisture content for the laboratory conditioned cellulose was found to vary between 4.16% and 5.16% with an average of 4.50%. For the desiccant conditioned cellulose, moisture content varied between 1.16% and 1.82% with an average of 1.47%. Several parameter combinations were tested over the course of multiple days without any significant deviation in results, indicating that small daily variations in moisture content do not have a significant effect on ignition propensity.

Figure 4 compares curves representing the lower limit of the flaming regime and the upper limit of the non-flaming regime for brass spheres at both moisture contents. These curves were created by curve-fitting the experimental data as described by Hadden *et al.* [8]. The curves found for stainless steel are very similar to the ones shown in Figure 4. The desiccant-conditioned cellulose appears to exhibit the same non-flaming limit as the laboratory conditioned cellulose but a slightly lower flaming limit. Further work is required to conclusively establish this trend, but it does indicate that increasing fuel bed moisture content decreases ignition likelihood for particles that would otherwise ignite, in agreement with the results found by Tanaka [9]. Water's high specific heat and enthalpy of vaporization would mean that increased moisture would hinder the amount of cellulose a particle could pyrolyze. Alternatively, the water may influence the kinetics of the nascent combustion reaction. The apparent independence of the non-flaming limit on moisture content suggests that moisture content does not strongly affect the possibility of ignition for a given combination of parameters but does influence the likelihood of a prone particle igniting in randomized tests.

www.witpress.com, ISSN 1743-3509 (on-line)

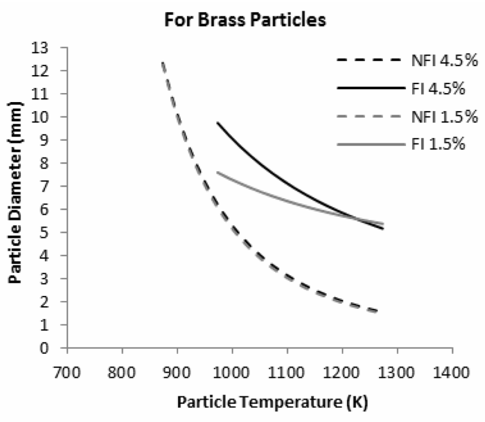


Figure 4: Effect of fuel bed moisture content on non-flaming and flaming ignition limits of brass particles.

3.3 Effect of particle thermal conductivity

Figure 5 maps non-flaming and flaming ignition limits similar to those in Figure 4 for stainless steel and brass particles at 1.5% moisture content. The stainless steel and brass particles produce very similar curves. The deviations that do exist are not significant in comparison to uncertainties associated with the small sample sizes and simple curve fit. This is also the case for tests carried out with 4.5% moisture content. The large difference in the metals' thermal conductivities

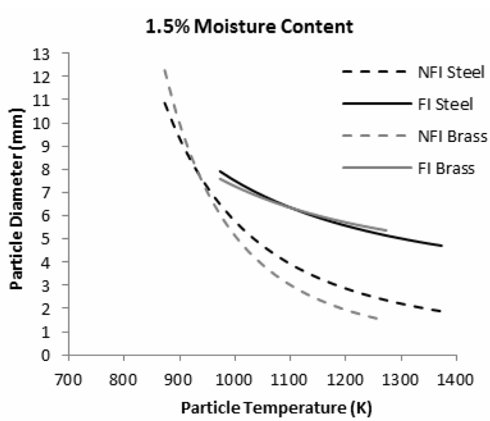


Figure 5: Effect of particle conductivity on non-flaming and flaming ignition with MC=1.5%.

www.witpress.com, ISSN 1743-3509 (on-line)

appears to be unimportant to the problem. This implies that, relative to the characteristic time associated with the particle, the ignition process either happens very slowly (i.e. bulk energy transfer from the sphere) or very rapidly (i.e. the temperature of the sphere is approximately constant).

4 Discussion

In the range under study, particle size and temperature seem to greatly affect ignition likelihood, while particle thermal conductivity and fuel bed moisture content are less influential. With this being the case, the non-ignition limit's independence from fuel bed moisture content may be due to the fact that some minimum threshold associated with diameter and temperature has not been met, making fuel bed attributes unimportant. Also, many factors considered random in this work, including local density of the fuel bed, penetration depth, and trajectory, may affect the local dependence on the parameters under study. This would explain the probabilistic nature of the experimental results and the existence of a possible flaming ignition regime.

5 Conclusion

Ignition of powdered cellulose fuel beds by hot spherical particles was studied experimentally. The effects of particle diameter, temperature and thermal conductivity as well as fuel bed moisture content were investigated by dropping stainless steel and brass spheres of different sizes and temperatures onto fuel beds of varying moisture content. Ignition propensity correlates positively with particle diameter and temperature, exhibiting asymptotic behavior for low temperatures (~873K) and small diameters (3.18 mm). Changes in moisture content seem to have a small effect on the boundary of the flaming regime over the range of moistures tested. Particle thermal conductivity does not appear to influence ignition behavior significantly. The results of this work suggest that the ignition of fuel beds by hot particles is most strongly dependent on the particle size and initial surface temperature.

Acknowledgements

The authors would like to thank Freddy Sevilla and Chris Lautenberger of Reax Engineering for their contributions to this work. This research was supported by National Science Foundation Award No. CBET-1066520.

References

[1] Karter, M., *Fire Loss in the United States during 2010*, National Fire Protection Association, pp. 2, 2011.

[2] Rein G., Cohen S. & Simeoni A., Carbon emissions from smoldering peat in shallow and strong fronts. *Proceedings of the Combustion Inst.*, eds. V. Sick & L.P.H. de Goey, Elsevier: Amsterdam, pp. 2489–2496, 2009.
[3] Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.V., Jaya, A. & Limin, S., The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature,* **420**, pp. 61–65, 2002.
[4] Finney, M.A., FARSITE: Fire Area Simulator-model Development and Evaluation, *Research Paper RMRS -RP4*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, 1998.
[5] Linn, R., Resiner, J., Colman, J.J. & Winterkamp, J., Studying wildfire behavior using FIRETEC. *Intl. Journal of Wildland Fire,* **11(4)**, pp. 233–246, 2002.
[6] Rowntree, G.W.G. & Stokes, A.D., Fire ignition by aluminum particles of controlled size. *Journal of Elec. and Electronics Engr., Australia,* **14**, pp. 117–123, 1994.
[7] Rallis, C.J. & Mangaya, B.M., Ignition of veld grass by hot aluminum particles ejected from clashing overhead transmission lines. *Fire Technology,* **38**, pp. 81–92, 2002.
[8] Hadden, R.M., Scott, S., Lautenberger, C. & Fernandez-Pello, A.C., Ignition of combustible fuel beds by hot particles: an experimental and theoretical study. *Fire Technology,* **47**, pp. 341–355, 2011.
[9] Tanaka, T., On the inflammability of combustible materials by welding splatters. *Unknown Japanese Journal*, pp. 51–58, 1977.