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The Influence of Fuel Surface Roughness on Ignition in the Mining Industry

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Abstract - Fuel surfaces found in mining industries will often be torn due to wear. The environment in mining industries is distinguished by functionality and not esthetical reasons, surfaces in these environments will be rougher than surfaces found in residential homes. Performing fire experiments and testing the ignition characteristics of the fuel surface, the influence of surface roughness and surface structures should be investigated and accounted for. Ignition would occur first at any part exposed by heat transfer from several directions and we are facing a two/three-dimensional ignition scenario. In this paper the gauge depth, angle and distance was varied to depict roughness. In five out of 13 experimental cases the average ignition time showed significant difference when compared to the flat surface case, but no clear pattern was detected. No clear patterns were found when studying the two-dimensional analysis results at the time of ignition. In both experiments and the two-dimensional analysis a majority of the temperatures were within the one standard deviation variation and did not show any significant difference compared with the flat case, except when comparing the gauge bottom temperatures and upper surface temperatures of the two-dimensional analysis where significant difference was found in all cases.

Keywords: Surface roughness, Ignition, Two dimensional, Cone calorimeter, Finite difference method.

1. Introduction

One of the most important data when quantifying a fire is the heat release rate of the fire. Knowing the heat release rate will in turn give vital information about the smoke spread, temperature distribution etc. When designing the overall heat release rate of for example a mining vehicle, calculating the appropriate ignition time of the various fuel packages on the vehicle will be decisive. During a number of earlier studies on the heat release rate of mining vehicles [1-2] the question on how the surface roughness will affect the ignition has been raised. The environment in mining industries is distinguished by heavy tear and rough fuel surfaces. The surface roughness magnitude of the gauges, dents etc. could be substantial, where the roughness depth would range from less than a millimeter up to several millimeters.

Any surface protuberances on an uneven surface would ignite first; as these will be exposed by heat transfer from several directions as we are facing a two/three-dimensional ignition scenario. See Thomas [3] for further details on surface roughness. Heskestad [4] performed ignition tests on samples with variable surface roughness and found that the ignition time was affected by the roughness. Akita [5] performed ignition tests on wood with variable surface roughness and found no differences in ignition time. These two studies point in different directions but the number of experiments in the papers was limited and the subject has not been investigated to any larger extent.

The work presented consists of an analysis where results from cone calorimeter experiments and a two-dimensional analysis were used for exploring potential relationships with respect to the ignition of rough fuel elements. The aim and purpose of this paper is to perform an exploratory analysis on the influence of surface roughness with respect to ignition that may act as a basis for future studies. Besides surfaces characterized by roughness, the results may also be applicable to non-flat surfaces where the surface structures are part of the design of the equipment such as tyre threads.

2. Ignition process

Ignition of a fuel item will depend on its flat surface reaching a critical condition such as a temperature. The ignition temperature represents the point in time when a flat surface can support flaming ignition [6-7]. For this critical condition to be reached, the incident heat flux has to exceed the surface losses at the ignition temperature. Surface roughness will then be expected to affect the local incident heat flux and the local surface losses. In turn the local temperature would be expected to vary based on the characteristics of the roughness.

3. Experiments and two-dimensional analysis

3.1. Cone calorimeter experiments

Cone calorimeter experiments were conducted in the Fire Science Laboratory at WPI.

The specimens were white pine boards (0.1x0.1x0.025 m (LxWxH)) as the surface would not change shape during the pre-ignition phase, exceeding the length scale of the roughness structures. Measurements were performed to verify thermally-thick behavior.

V-shaped gauges were milled in the same direction as the grain - depicting roughness features - varying the depth, angle and distance; see Table 1 and Figure 1. Table 1 also includes the normalized characteristic lengths of the cases, with respect to the width/length of the cone specimen (i.e. 100 mm). The limited data set was due to the scoping study nature of the project.

Case #1 had no roughness feature for reference. Throughout the experiments the incident heat flux was set to 35 kW m^{-2}.

The ignition time, temperature on upper surface and in a gauge (using glass braid insulated thermocouples with 0.25 mm diameter and a 2.2°C tolerance) were recorded. The thermocouples in the gauges were positioned in the upper third part of the gauge as it was difficult to position the thermocouples at the bottom.

The average specimen moisture content was measured at 5.8%, using a P-2000 electrical resistance-type moisture meter from Delmhorst Instrument.

Outlier elimination of ignition times and surface temperatures were conducted as single values stood out. When outlier elimination was applied the change in the average value was minimal.

When looking into the temperature data of the cone experiments it was noticed that when the shutter opened a sudden temperature increase occurred followed by a period where the temperature levelled out and finally a rapid temperature increase. An ignition criterion was defined in this paper as the point of time when the temperature initiated this final and sudden increase.

3.2. Finite Difference Method

A two-dimensional analysis – applying a finite difference methodology – of the heat conduction into the specimen was conducted, varying: gauge depth, angle and distance. Table 2 lists the different cases, identical with the experiments.

Unsteady-state conduction and no energy generation were assumed. Neglecting heat of pyrolysis and assuming an opaque material, the energy equation of the solid phase:

$$\rho_s c_{p,s} \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T_s}{\partial y}\right) \tag{1}$$

was applied, where $c_{p,s}$ is the specific heat of solid (kJ kg^{-1} K^{-1}), k is the thermal conductivity (kW m^{-1} K^{-1}), t is time (s), T_s is the surface temperature (K), x and y are the distances to point of interest (m) and ρ_s is the density of solid (kg m^{-3}).

Exposed face solid boundary condition was applied:

$$-k \frac{\partial T}{\partial x} = h_c \cdot (T_0 - T_s) + \dot{q}''_{net,rad,enclosure} \tag{2}$$

where h_c is the convective heat transfer coefficient (kW m^{-2} K^{-1}), $\dot{q}''_{net,rad,enclosure}$ is the net radiation term for the upper surface ($x = 0$) (kW m^{-2}), T is the temperature (K) and T_0 is the ambient air temperature (K).

The roughness parameters can be linked to equation (2). The convective heat transfer, first term on right hand side of equation (2), is assumed constant relative to the surface roughness due to the "shallow" normalized depths (up to 5%). The radiation heat transfer, second term on the right hand side of equation (2), accounts for the changing aspects of the surface roughness. It is assumed that the incident radiation to each node varies with the radial distance from the centre of the specimen. It is also assumed that the incident radiation inside a gauge enclosure will vary with the gauge angle and depth. Each upper surface node shown in Figure 1 exchanges radiation with the ambient environment only. Each surface node that is part of a gauge, see Figure 1, exchanges radiation with the ambient and the other parts of the gauge that can be "seen" from the given node. A virtual enclosure is established for each gauge based on its characteristics and the appropriate view factors are calculated to establish the radiative exchange "within" the virtual enclosure.

See Hansen and Dembsey [8] for the enclosure analysis of the radiant term, the governing equations for the rough surface interface exposed to radiant heating details, the node equations and set up of analysis.

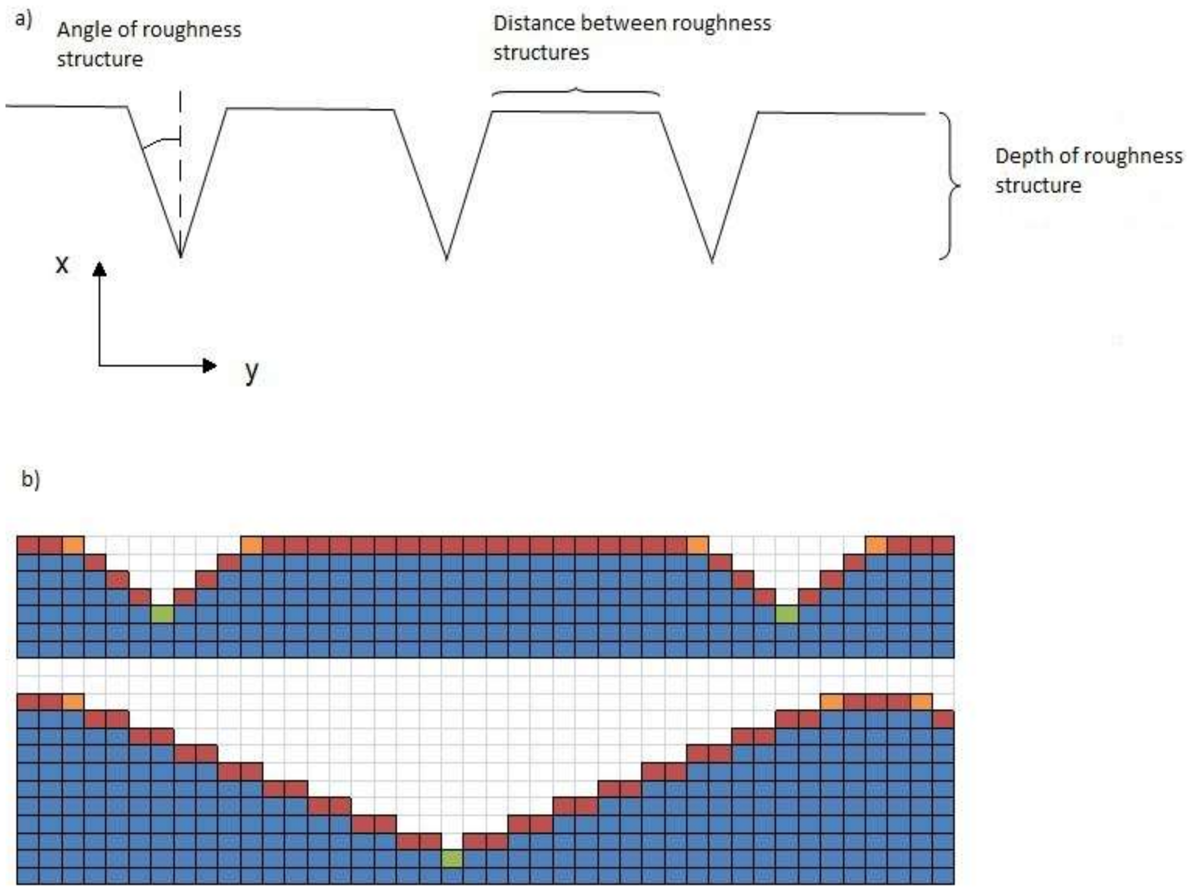

Fig. 1: (a) Characterization of the surface roughness applied in the experiments and analysis. (b) Node set-up in two cases. The blue squares represent interior nodes, the red surface nodes, the orange exterior corner nodes and the green interior corner nodes.

Table 1: The configuration of each experimental case; resulting ignition times and temperatures of the experiments.

Case #	Depth of gauges (mm)	Angle of gauges (degree)	Distance between gauges (mm)	Number of Gauges	Normalized depth	Normalized distance	Average ignition time (s)	Standard deviation ignition time	Average upper surface temperature (°C)	Standard deviation upper surface	Average gauge temperature (°C)	Standard deviation gauge temperature
1	0	0	0	0	0	0	30	2	364	20	-	-
2	2	45	10	5	0.02	0.1	34	2	404	18	384	10
3	5	45	10	4	0.05	0.1	41[1]	2	411[2]	16	371[4]	20
4	2	45	2	9	0.02	0.02	30	2	346	25	365	13
5	5	45	2	5	0.05	0.02	40[1]	4	360	20	356	12
6	2	30	10	5	0.02	0.1	26	2	370	23	346	25
7	5	30	10	4	0.05	0.1	31	3	377	40	314[43]	20
8	2	60	10	4	0.02	0.1	17[1]	1	313[2]	22	300[3]	14
9	5	60	10	3	0.05	0.1	30	4	363	20	345	16
10	2	30	2	8	0.02	0.02	26	1	361	14	359	25
11	5	30	2	6	0.05	0.02	35[1]	4	364	16	336	29
12	2	60	2	6	0.05	0.02	31	3	361	19	368	18
13	5	60	2	4	0.05	0.02	28	2	344	15	353	20
14	2	30	20	3	0.02	0.2	25[1]	1	390	6	336[4]	16
								Avg = 2		Avg = 20		Avg = 18

4. Results

Establishing a significant difference between the mean experimental values, a criterion where the range of one standard deviation of the means did not overlap each other was applied, see Table 1.

4.1. Ignition times of experiments

Table 1 displays the average time of ignition for all experimental cases. Five of the 13 cases showed significant difference when compared to the flat surface case. These 5 cases did not show any clear pattern related to the gauge characteristics. The ignition times were observed visually with an estimated tolerance of 1 s.

4.2. Surface temperatures at ignition from experiments

Table 1 displays the average upper surface and gauge temperatures for all experimental cases. Two out of 13 cases for the upper surface temperature, and two out of 13 cases for the gauge temperature showed significant difference when compared to the flat case. These cases show no clear pattern related to the gauge characteristics. Comparing the upper surface and gauge temperatures for each case showed significant temperature difference in 3 out of 13 cases. These cases show no clear pattern related to the gauge characteristics. The tolerance of the applied thermocouples was 2.2°C.

4.3. Surface temperatures at t=25 s from two-dimensional analysis

Table 2 displays the average node temperatures at t=25 s from the two-dimensional analysis. This fixed time will be used to verify the two-dimensional analysis. The point of time at t=25 s was selected as it was just prior to the ignition of a

[1] Shows significant difference based on 1 SD variation (4 sec) compared to Case #1 for ignition time.
[2] Shows significant difference based on 1 SD variation (40 °C) compared to Case #1 for upper surface temperature.
[3] Shows significant difference based on 1 SD variation (36 °C) compared to Case #1 for gauge temperature.
[4] Indicates significant difference based on 1 SD variation (38 °C) between upper surface and gauge temperatures.

majority of the experiments and distinct temperature differences had been established at that time. The average upper surface temperature was the average surface node temperatures between two gauges in the centre of the sample. The upper 1 mm gauge slope temperature was the average surface node temperatures for a corner node and the corresponding nodes below it into the gauge for a distance of 1 mm. The average gauge bottom temperature was the node temperatures of the bottom node. The location of both these temperatures was the gauge closest to the specimen centre.

The upper surface and upper 1 mm gauge temperature increase as gauge depth increases for all angles and spacing. This is consistent with the fact that the net difference between heating (incident heat flux from cone and re-radiation within gauge) and cooling (convective cooling and re-radiation out of the gauge) increases with increasing depth.

The gauge bottom temperature decreases as the gauge depth increases for all angles and spacing. This is consistent with the fact that the view factor from the cone heater to the bottom node always decreases with increasing depth and the view factor from opposite gauge slope to bottom node also decreases with increasing depth.

The upper surface and upper 1 mm gauge temperatures decrease as gauge spacing increases for all angles and depths - except the 30 degree cases with a 2 mm gauge depth. This is consistent with the fact that the temperatures of the edge nodes are generally higher than the upper surface temperature as the edge node is exposed to heat flux from two directions. With increasing gauge distance between edge nodes, the upper surface temperature will decrease as edge node heating effect decreases. With a longer distance between two edge nodes, the cooling effect of the upper surface will increase and result in lower upper 1 mm gauge temperatures. The edge node temperatures in the 30 degree and 2 mm depth cases are lower than the upper surface temperatures as the net difference between heating and cooling is lowest for the 30 degree cases.

The gauge bottom temperature decreases or does not change as gauge spacing is increased for all angles and depths - except for the 30 degree cases. This is consistent with the fact that variations of the gauge distance will influence the upper nodes and upper surface but not the gauge bottom to the same degree. In the 30 degree cases - as the edge node has a lower temperature - an increasing spacing will result in higher upper surface temperature which will effect to some extent the gauge bottom temperature.

The upper surface, the upper 1 mm gauge and gauge bottom temperatures all increase with increasing gauge angle for all depths and spacing. The upper region temperature increase has a peak at a gauge angle of 60 for the 2 mm depth and at a 45 angle for the 5 mm depth. This is consistent with an increase in the surface area and that the net difference between heating and cooling increases as the gauge angle increases. As the depth increases a larger portion of the radiative energy is re-radiated from nodes in the upper slope region to the lower nodes in the 60 degree case than for the 45 or 30 degree cases.

Given the results of the model at t=25 s, the output of the model were found to be consistent with the definition of the boundary conditions and the virtual enclosures for the gauges.

4.4. Surface temperatures at ignition from two-dimensional analysis

Table 2 displays the average temperatures at the time of ignition from the two-dimensional analysis. The upper third gauge slope temperature was calculated for comparison with the experimental results as the thermocouples in the gauges were positioned in this part of the slope. The upper third gauge slope temperature was the average surface node temperatures for a corner node and the corresponding nodes below it into the gauge for a distance of one third of the total slope length. The location of the temperature was the gauge closest to the specimen centre. The upper surface and gauge bottom average temperatures are defined the same as previously noted for the t=25 s discussion.

The significant difference of the model was defined as the level of significance of the experimental data - one standard deviation - which can be seen in Table 1. Use of the experimental standard deviations is reasonable as a model cannot be verified or validated to a level of uncertainty better than the available experimental data.

When studying the ignition times in Table 2, six out of 13 cases for the upper surface temperature showed significant difference when compared to the flat case. In all but one of these cases the gauge distance were 2 mm. Five out of 13 cases for the upper third gauge slope temperature showed significant difference when compared to the flat case. These cases show no clear pattern related to the gauge characteristics. Comparing the upper surface and upper third gauge slope temperatures for each case showed significant temperature difference in two out of 13 cases. Both of these two cases represent the 30 degree angle and 5 mm depth cases. These results of the two-dimensional analysis are similar to the experiments where for a minority of cases significant differences are observed due to changes in gauge characteristics.

Gauge bottom temperature behavior is similar to that noted for t=25 s. When comparing the gauge bottom temperatures with the corresponding upper surface temperatures significant difference was found in all cases.

Table 2: The average upper surface and gauge temperatures at ignition from the two-dimensional analysis.

Case #	Average upper surface temp. at ignition (°C)	Average upper third gauge slope temp. at ignition (°C)	Average gauge bottom temp. at ignition (°C)	Average difference in temp.: upper surface and upper third gauge slope at ignition (°C)	Average difference in temp.: upper surface and gauge bottom at ignition (°C)	Average upper surface temp. at t=25 s (°C)	Average gauge bottom temp. at t=25 s (°C)	Average upper 1 mm gauge slope temp. at t=25 s (°C)
1	316	-	-	-	-	303	-	-
2	341	341	215[8]	0	126	317	188	317
3	365[5]	363[6]	186[8]	2	179	323	152	339
4	361[5]	346	214[8]	15	147	346	195	330
5	407[5]	381[6]	188[8]	26	219	368	152	358
6	309	273[6]	135[8]	36	174	308	134	262
7	335	289[7]	93[8]	46	242	318	84	298
8	285	290	172[8]	-5	113	319	204	326
9	334	326	204[8]	8	130	320	191	331
10	308	277[6]	140[8]	31	168	305	135	262
11	371[5]	317[7]	104[8]	54	267	350	87	318
12	370[5]	350	227[8]	20	143	354	207	338
13	367[5]	330	198[8]	37	169	360	191	345
14	308	273[6]	135[8]	35	173	307	133	262

4.5. Comparison of experiments and results from two-dimensional analysis

When comparing the temperatures at time to ignition found in Table 1 and Table 2, only in two cases did the temperatures show significant difference coinciding in both experiments and the two-dimensional analysis. These cases show no clear pattern related to the gauge characteristics. In both experiments and two-dimensional analysis a majority of the temperatures were within the one standard deviation variation and did not show any significant difference compared with the flat case.

For an analysis and discussion on the surface temperature distribution at ignition and decomposition zones and isosurface plots, see Hansen and Dembsey [8].

5. Conclusions

[5] Shows significant difference based on 1 SD variation (40°C) compared to Case #1 for upper surface temperature.
[6] Shows significant difference based on 1 SD variation (36 °C) compared to Case #1 for upper third gauge slope temperature.
[7] Indicates significant difference based on 1 SD variation (38 °C) between upper surface and upper third gauge slope temperatures.
[8] Indicates significant difference based on 1 SD variation (38 °C) between upper surface and gauge bottom temperatures.

It was found that in five out of 13 experimental cases the average ignition time showed significant difference when compared to the flat surface case, but no clear pattern related to the gauge characteristics was detected.

Two out of 13 experimental cases for the upper surface and the gauge temperature showed significant difference when compared to the flat surface case. These cases showed no clear pattern related to the gauge characteristics. Comparing the upper surface and gauge temperatures for each case showed significant temperature difference in three out of 13 cases, again no clear pattern was detected.

Verifying the two-dimensional analysis, the resulting output were found to be consistent with the definition of the boundary conditions and the virtual enclosures for the gauges.

When studying the analysis results at the time of ignition, six out of 13 cases for the upper surface temperature showed significant difference. Five out of 13 cases for the upper third gauge slope temperature showed significant difference, but no clear pattern was detected. Comparing the upper surface and upper third gauge slope temperatures showed significant temperature difference in two out of 13 cases.

When comparing the experimental results with the analysis results, only two cases showed significant temperature difference and coincided in both experiments and analysis.

In both experiments and the two-dimensional analysis with normalized roughness features in the range 2% to 10% a majority of the temperatures were within the one standard deviation variation and did not show any significant difference compared with the flat case, except when comparing the gauge bottom temperatures and upper surface temperatures of the two-dimensional analysis where significant difference was found in all cases.

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