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# IGNITION RISKS OF BIOMASS DUST ON HOT SURFACES

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## ABSTRACT

Combustible biomass dusts are formed at various handling stages and accumulations of these dusts can occur on hot surfaces of electrical and mechanical devices and can pose fire risks. This study evaluates the ignition characteristics of dust from two types of biomass commonly used in the U.K. power stations – herbaceous miscanthus and woody pine. The ignition risks of the individual biomass and their blends in two different weight ratios – 90wt% pine to 10wt% miscanthus and 50wt% pine to 50wt% miscanthus were investigated. Biomass-biomass blends represent the power plants scenario where a number of biomass are fired under daily operation and thus, dust sedimentation could consist of material blends. The influence of washing pre-treatment (particularly to remove catalytic potassium) on the ignition behavior of these dusts was investigated. Fuel characterization via proximate and ultimate analyses was performed on all fuels and combustion characteristics via thermogravimetric analysis (TGA). The risk of self-ignition propensity of both untreated and washed biomass were ranked graphically by utilizing the activation energy ($E_a$) for combustion and the temperature of maximum weight loss ($T_{MWL}$) determined from the derivative TGA (DTG) curve. It was found that the $T_{MWL}$ and $E_a$ of washed biomass were higher than those of the untreated biomass, implying a lower self-ignition risk. Similar analyses were done on untreated and washed blends and comparable results were observed. The ignition characteristics were studied following the British Standard test methods for determining the minimum ignition temperature of a 5-mm dust layer on a heated surface. It was found that the washed individual biomass and their blends revealed slightly higher dust ignition temperatures than their respective untreated counterparts; a 20°C and 10°C difference for individual biomass and blends respectively. The effect of washing on ignition delay time was more obvious for pine than for miscanthus, but the time difference between the untreated and washed biomass never exceed four minutes for all biomass and blends. The biomass pre-treatment method of washing did change the combustion and self-ignition characteristics of biomass dust, and there was evidence of potassium being leached from the fuels upon washing (particularly miscanthus). This is considered the main reason for the increase in minimum ignition temperature. While the washed biomass is found to have a lower ignition risk, it should be noted that the result (validated for up to 5 mm thickness) is not significant enough to influence plant operations for the ignition risk from thin dust layers according to the National Fire Protection Association (NFPA) Standards.

**KEYWORDS.** Combustible dust, minimum ignition temperature, ignition delay time, washing, catalytic effect

## 1. INTRODUCTION

The world energy demand has been fulfilled mainly by non-renewable fossil fuels like coal and oil. However, these resources are depleting and their extensive use is affecting global atmospheric carbon dioxide ($CO_2$) concentrations. In the United Kingdom (U.K.), firing biomass or co-firing biomass with coal serves as a partial solution to reducing $CO_2$ emissions and fulfilling the commitment to reduce greenhouse gas (GHG) emissions by 50% by 2020.

Unfortunately, biomass is a reactive solid fuel capable of self-heating and self-igniting. In the utilization of biomass, combustible biomass dust can accumulate on hot surfaces of many electrical and mechanical devices like conveyers, dryers, hot bearings and other machinery. Thus, good housekeeping is critical in keeping surfaces clean and minimizing accumulation of dust. The dust can be formed during various handling stages from the source to end use – during transportation, preparation, usage and storage. Both dust suspensions and dust sediment pose fire hazards, but this work concerns the latter. There have been many incidents globally of biomass fires, for example, in October 2013, a fire broke out at the Port of Tyne in South Shields, South Tyneside involving a fire outbreak in a conveyor transfer tower storing biomass[1].

In normal power station operation, different types of biomass are included in the fuel inventory, and thus the dust formed might consist of blends of biomass. Many researchers have identified potential synergy in the combustion characteristics of biomass-coal blends, whereby the more reactive biomass can enhance the reactivity of the less reactive material. In the study of Mortari *et al.*[2] where the ignition temperatures of sugar cane bagasse, coal and their blends were studied, it was found that the bagasse/coal blends ignited at 275°C, a temperature much closer to the ignition temperature of the more reactive fuel i.e. bagasse. They concluded that the synergetic effects when both fuels were blended had actually changed the overall fuel reactivity. Ignition and reactivity studies by Wilén *et al.*[3] on two fuel blends which consisted of biomass and low grade coal (lignite) also found that the blends of lignite with biomass had resulted in an overall blend reactivity comparable to lignite, which was the most reactive fuel in their study. The ignition temperature of two different biomass-lignite blends showed ignition temperatures much closer to that of lignite. It is therefore important to consider the ignition characteristics of dusts from biomass blends as well as dust from just a single type of biomass.

It has been concluded in other studies that potassium minerals that occurs naturally in biomass have a catalytic effect[4] that plays an important role in influencing the combustion characteristics of biomass fuel. Washing of biomass is a recognized pretreatment method that removes many of the undesired minerals and salts within the biomass fuel and subsequently enhances the biomass combustion characteristics by improving ash behavior[5]. An interesting question for research is whether the decreased reactivity of water-washed fuel impacts on ignition risk – i.e. does pretreatment via water-washing make the biomass an inherently safer fuel?

There is very little data in the literature concerning critical ignition temperatures and ignition delay times of biomass dust layers, both for pure biomass dusts and for biomass dust blends. Similarly, there is no data concerning the impact of pretreatment on these. This paper therefore addresses a gap in knowledge.

## 2. EXPERIMENTAL SECTION

### *2.1 Sample Preparation.*

The two different types of biomass, i.e. herbaceous miscanthus and woody pine were obtained from two different U.K. power stations. The biomass were divided into two portions of equal weights, and the first category was left untreated while the second was pre-treated. The pre-treatment involved washing of biomass with distilled water in a 1:5 ratio (biomass:water). In this study, every 1 g of fuel (miscanthus or pine) was washed with 5 ml of distilled water for 60 minutes at room temperature by stirring at 500 rpm in a beaker. After washing, the wet biomass was filtered and the leachate retained for further analysis. Both the untreated and pre-treated (washed) biomass were dried to constant weight at 80°C in an oven.

All dried solid biomass was milled to finer particle size using the Retsch PM 100 Ball Mill and sieved before taken for fuel characterization and combustion characteristics experiments. Any sample that did not pass through the sieves underwent the milling process again. Thus, all materials were milled to <180 μm.

Blends were produced from both untreated and washed fuels with 90 wt% pine and 10 wt% miscanthus (PM9010) and 50 wt% pine and 50 wt% miscanthus (PM5050). These steps were applied to both the untreated and washed biomass to produce eight different biomass for analysis – untreated pine (Pine), washed pine (PineW1hr), untreated miscanthus (Misc), washed miscanthus (MiscW1hr), untreated 90wt% pine-10wt% miscanthus (PM9010), washed 90wt% pine-10wt% miscanthus (PM9010W1hr), untreated 50wt% pine-50wt% miscanthus (PM5050) and washed 50wt% pine-50wt% miscanthus (PM5050W1hr). The names in parentheses will be used hereafter.

### *2.2 Solid Fuel Characterization – Proximate Analysis, Reaction Rate Kinetics, Self-Ignition Risk Ranking and Ultimate Analysis.*

The proximate analysis was estimated via a thermogravimetric (TGA) burning profile method using a TA Q5000. The materials used in TGA were <90μm to give a sufficiently low Biot number [6], and the particles size distribution showed less than 10% were finer than 10μm. Approximately 4 mg of pulverised materials were loaded on the microbalance and the slow combustion procedure was applied. The sample was heated in air at a rate of 5°C/min to 105°C and held isothermally for 10 minutes, to determine the moisture content. The sample was then heated at 5°C/min to a final temperature of 800°C and held for 10 min. This analysis for each material was done in duplicate or triplicate. Mass loss as a function of temperature was obtained.

Ramirez et al. developed a self-ignition risk ranking method from burning profiles in oxygen[7]. Modifications were made to this approach, since here, experiments are conducted in air. Hence, the single oxidation temperature used by Ramirez et al. ($T_{charac}$) was replaced in this study by the temperature of the maximum rate of weight loss temperature ($T_{MWL}$) in air stream. As discussed in the study on low temperature ignition of biomass by Jones et al. [8], a single peak, $T_{charac,}$ was not observed in TGA studies under oxygen. The apparent first order activation energy, $E_a$, was calculated from the TGA weight loss curve and this parameter was also used in the risk ranking method. This followed the reaction rate kinetics calculation used by Ramirez et al. [7] and Saddawi et al. [9], where it is assumed that the volatile combustion can be treated as a first order reaction in terms of sample mass. A typical burning profile is given in Figure 1. The $T_{MWL}$ and the section selected for kinetics calculation are illustrated in Figure 1. With both the $T_{MWL}$ and $E_a$ known, the self-ignition propensity of all the eight biomass samples in this study could be ranked using the modified pictorial ranking method used by Ramirez et al. [7].

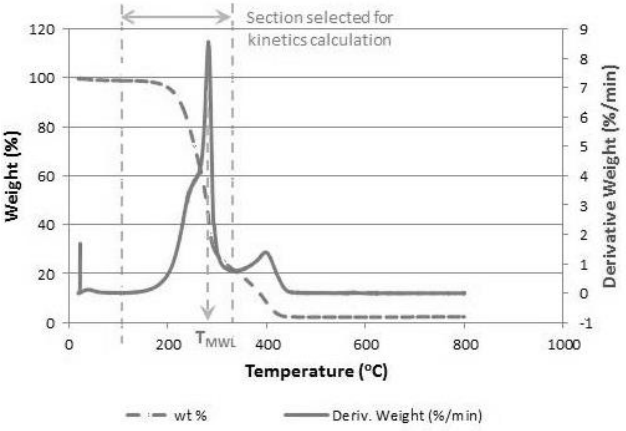


**Figure 1.** Biomass $T_{MWL}$ and the section selected for kinetics calculation

Ultimate analysis was performed using a FLASH EA1112 Elemental Analyzer. The weight percentages of carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) were obtained and oxygen (O) content was then determined by difference from 100% - ash - moisture. After obtaining the values on dry basis, the higher heating value (HHV) of each biomass was calculated by employing the empirical correlation from Friedl et al.[10], that is: $\mathrm{HHV} = 3.55C^2 - 232C - 2230H + 51.2\,CH + 131N + 20600$, in which HHV is in the unit of kJ/kg. The correlation had been previously validated with bomb calorimetry experiment[10-11].

### 2.3 Solid Fuel Chemical Element Determination – Acid Digestion and Atomic Absorption Spectroscopy (AAS).

Both the untreated biomass materials were acid digested in concentrated sulphuric acid ($H_2SO_4$) and concentrated nitric acid ($HNO_3$) at 200 °C for 30 min, then 250 °C for 30 min. Digestate was diluted to 100 ml and potassium and calcium in the diluted sample was determined via Atomic Absorption Spectroscopy (AAS) using a Varian FS 240 Atomic Absorption Spectrophotometer.

*2.4 Filtrate Analysis – Ion Chromatography (IC).* After washing, the leachates were analyzed by ion chromatography for the cations (especially potassium and calcium) and anions (especially chloride) using a Dionex DX100 Ion Chromatograph.

### 2.5 Determination of Ignition Characteristics of Solid Biomass Dust Layers.

The minimum dust layer ignition temperature and the corresponding dust layer ignition delay time were measured in accordance with British Standard BS EN 50281-2-1:1999 Electrical apparatus for use in the presence of combustible dust, in which part 2-1 contains test methods dedicated to determining minimum ignition temperatures and ignition delay time of a biomass dust subjected to a predefined hot surface temperature.

The dust layer apparatus (ANKO) consists of a heated plate connected to a temperature controller that is connected to a computer acting as a recorder unit. There are two sets of Type K thermocouple used in this apparatus – hot plate thermocouples and the dust layer thermocouple. The heated plate aims to provide a uniform temperature over its surface, and a metal ring is used to contain the dust layer top of the plate. A fine thermocouple is stretched parallel across the surface of fine dust layer at a height of around 2 to 3 mm above the plate, and adjusted such that its junction was located at the geometric center of the heated plate.

The hot plate was set to an estimated dust ignition temperature and once the set temperature was achieved and stabilized, the biomass dust was poured into the metal ring and levelled off within 2 minutes; at this point the data logger and stop watch were started simultaneously. According to the standard method, dust layer ignition is recognized when either of these is achieved: i) flaming or glowing in material is seen, ii) material temperature of 450$^{o}$C or higher is measured and iii) a material temperature rise of at least 250$^{o}$C above the prescribed hot plate temperature. In this study, ignition was recognized once visible glow was observed. The critical ignition temperature is the lowest heated plate temperature (that was set in steps of 10$^{o}$C) when a glow was seen for a specific dust layer thickness. A fresh dust layer was used every time whether the dust ignited or did not. The criterion used in deciding the next heated plate temperature depended on whether ignition had been observed previously: Following the 10$^{o}$C interval suggested in the test standard, if ignition had been observed, the hot plate temperature was lowered by 10$^{o}$C; on the other hand, if no ignition had been seen within 30 minutes, the heated plate temperature was increased by 10$^{o}$C. At the lowest hot-plate temperature which ignition had been seen, that particular hot plate temperature was reduced by 10$^{o}$C and used for a total of three times on fresh dust layers for confirmation that no ignition occurs at the lower temperature. The lowest dust ignition temperature, time taken for material to ignite, and type of ignition seen were all recorded.

## 3. RESULTS AND DISCUSSION

### *3.1 Solid Fuel Characterization.*

The result for TGA proximate analysis of the eight biomass materials studied is shown in Table 1. Since all biomass were dried as described in Section 2.1, the moisture contents were similar and less than 2 wt%. The ash content in the miscanthus was high (more than 10 wt%) and this reduced considerably after the washing pre-treatment. Although the ash content was almost halved, it is still high compared with the other materials. It was also noticed that water-washing pre-treatment increased the volatile matter but decreased the fixed carbon content. These results are consistent with the findings from the study of Nowakowski *et al.* [12] on short rotation willow coppice, in which the pre-treated willow showed increased volatiles and decreased char with respect to the untreated material. The increased char formation from a demineralized sample impregnated with potassium led to the conclusion that potassium has a crucial effect on char formation by catalyzing the pyrolysis stage. It is believed that the presence of catalytic potassium promotes char formation at the expense of volatiles and thus, removal of this metal decreases fixed carbon formation.

The ultimate analyses are given in Table 2, together with the calculated high heating value using the method described in Section 2.2. The S content was not reported because the results of all biomass materials were below the detection limit of the instrument. On a dry basis, the effect of washing is to increase C and H and decrease N content. As a consequence of increased C and H contents, the HHV is also seen to increase upon washing. The biggest benefits of washing pretreatment were observed for Miscanthus.

**Table 1.** TGA Proximate Analysis of the Biomass Materials (wt% a.r.). Refer to Section 2.1 for sample designation

| Material | Moisture | Volatile Matter | Fixed Carbon | Ash |
|---|---|---|---|---|
| Pine | 1.8±0.1 | 79.2±0.7 | 18.1±0.2 | 1.0±0.4 |
| Misc | 1.8±0.6 | 71.5±0.7 | 15.9±0.7 | 10.8±0.6 |
| PM9010 | 1.8±0.6 | 80.3±0.7 | 17.5±0.1 | 0.5±0.3 |
| PM5050 | 1.3±0.2 | 82.5±0.2 | 13.7±0.2 | 2.5±0.1 |
| PineW1hr | 1.33±0.01 | 80.465±0.007 | 17.733±0.003 | 0.468±0.008 |
| MiscW1hr | 1.37±0.01 | 77.2±0.5 | 15.7±0.6 | 5.65±0.02 |
| PM9010W1hr | 1.4±0.5 | 80.7±0.8 | 16.7±0.1 | 1.3±0.5 |
| PM5050W1hr | 1.245±0.002 | 82.40±0.07 | 13.6±0.4 | 2.8±0.4 |

**Table 2.** Ultimate Analysis (wt%, a.r.) and calculated HHV (MJ/kg, d.b.) of the biomass samples

| Material | C | H | N | HHV |
|---|---|---|---|---|
| Pine | 44.98±0.04 | 5.9±0.2 | 0.16±0.02 | 18.13 |
| Misc | 41.6±0.6 | 5.58±0.07 | 0.713±0.009 | 16.89 |
| PM9010 | 47.6±0.9 | 6.3±0.2 | 0.162±0.003 | 19.31 |
| PM5050 | 46.279±0.003 | 6.08±0.02 | 0.324±0.002 | 18.63 |
| PineW1hr | 46.1±0.8 | 5.95±0.06 | 0.13±0.03 | 18.49 |
| MiscW1hr | 44.0±0.9 | 5.7±0.3 | 0.63±0.05 | 17.71 |
| PM9010W1hr | 48.1±0.1 | 6.28±0.08 | 0.135±0.009 | 19.44 |
| PM5050W1hr | 47.4±0.3 | 6.14±0.02 | 0.284±0.006 | 19.08 |

*3.2 Potassium and Calcium Contents.*

Pine and Misc were subjected to acid digestion experiment and the K and Ca contents of the diluted digestate were measured via AAS. These results are given in Table 3. After digestion, the Pine and Misc digestate solutions were yellow. Miscanthus contained nearly ten times more potassium and calcium compared to pine. Pretreatment via washing reduces both potassium and calcium concentrations, with the percentage removed being more significant for miscanthus.

*3.3 Leachate Analysis.*

The leachate collected from water washing was analysed via ion chromatography and results are given in Table 3. The leachate from miscanthus washing needed a ten time dilution. Leachate analysis indicates that a large fraction of potassium (and chloride) was removed from the miscanthus, and smaller, but significant percentages removed from pine. These results are in keeping with previous work[4] where 62 and 19 % removal of K and Ca respectively, and 80% Cl removal were found for miscanthus chips. The % removal from pine is similar to those obtained for willow and eucalyptus chips[4] i.e. 45-46% K, and 3-4% Ca. Table 3 shows the original element contents in the untreated fuel (determined by AAS); the cations $K^+$, $Ca^{2+}$, anion $Cl^-$ found in the leachates (detected by IC) and thus the calculated % removal.

**Table 3.** Concentration (mg/kg dry fuel) in untreated fuels (AAS analysis) and K, Ca and Cl removed (mg/kg dry fuel) during water washing (IC analysis of leachates)

| | **K** | **Ca** | **$K^+$ removed** | **% K removal** | **$Ca^{2+}$ removed** | **% Ca removal** | **$Cl^-$ removed** |
|---|---|---|---|---|---|---|---|
| Pine | 342 | 584 | 130 | 38 | 19 | 3 | 31 |
| Misc | 2998 | 5409 | 2709 | 90 | 1017 | 18 | 2781 |

*3.4 Risk ranking via TGA Analysis.*

A typical DTG profile is given in Figure 1. This data was used to obtain the $T_{MWL}$ for each biomass and the activation energy for devolatilisation by applying the reaction rate kinetics calculation method used in Ramírez et al.[7] and Saddawi et al.[9]. These are listed in Table 4. Consistent with results in studies of Saddawi et al.[4, 13] and Fahmi et el.[4, 13], $T_{MWL}$ of the washed samples shift to the right, i.e. the temperature of maximum rate of weight loss happens at a higher temperature. It is believed that the decrease in reactivity of the washed fuels and blends are the result of loss of catalytic K and Ca during washing. The decrease in reactivity upon washing is more significant for miscanthus than for pine.

**Table 4.** Reactivity parameters, $T_{MWL}$ (°C) and $E_a$ (kJ/mol) of the biomass materials

| **Material** | **$T_{MWL}$ (°C)** | **$E_a$ (kJ/mol)** |
|---|---|---|
| Pine | 288.4±0.4 | 79.3±0.9 |
| Misc | 272.2±0.4 | 80.3±0.1 |
| PM9010 | 288.6±0.6 | 82.8±0.1 |
| PM5050 | 287.0±0.5 | 86.5±0.7 |
| PineW1hr | 290.24±0.07 | 84.0±0.9 |
| MiscW1hr | 285.0±0.7 | 83.7±0.9 |
| PM9010W1hr | 289.7±0.9 | 84.79±0.02 |
| PM5050W1hr | 288.6±0.3 | 86.9±0.6 |

Fuels were evaluated for ignition risk following the definitions given in Ramírez et al.[7] and this is given in Figure 2. All fuels fall in the "high risk" category and pretreatment via washing has only a small effect on the self-ignition risk. In all cases, the fuels and the blends are less reactive upon pretreatment, especially for miscanthus, but the predicted ignition risk remains unchanged – i.e. still high risk. This is because the ranges of both $T_{MWL}$ and $E_a$ values were quite small for the untreated and washed biomass used in this study.

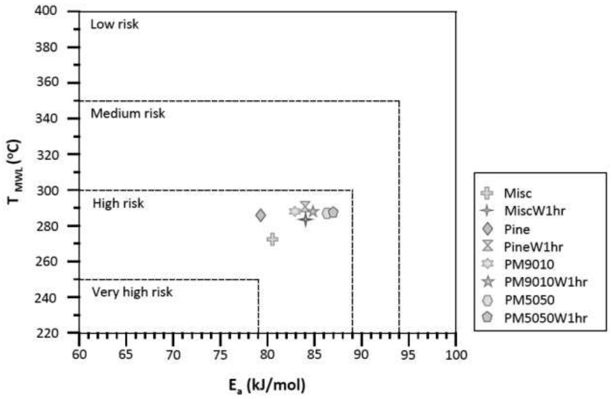
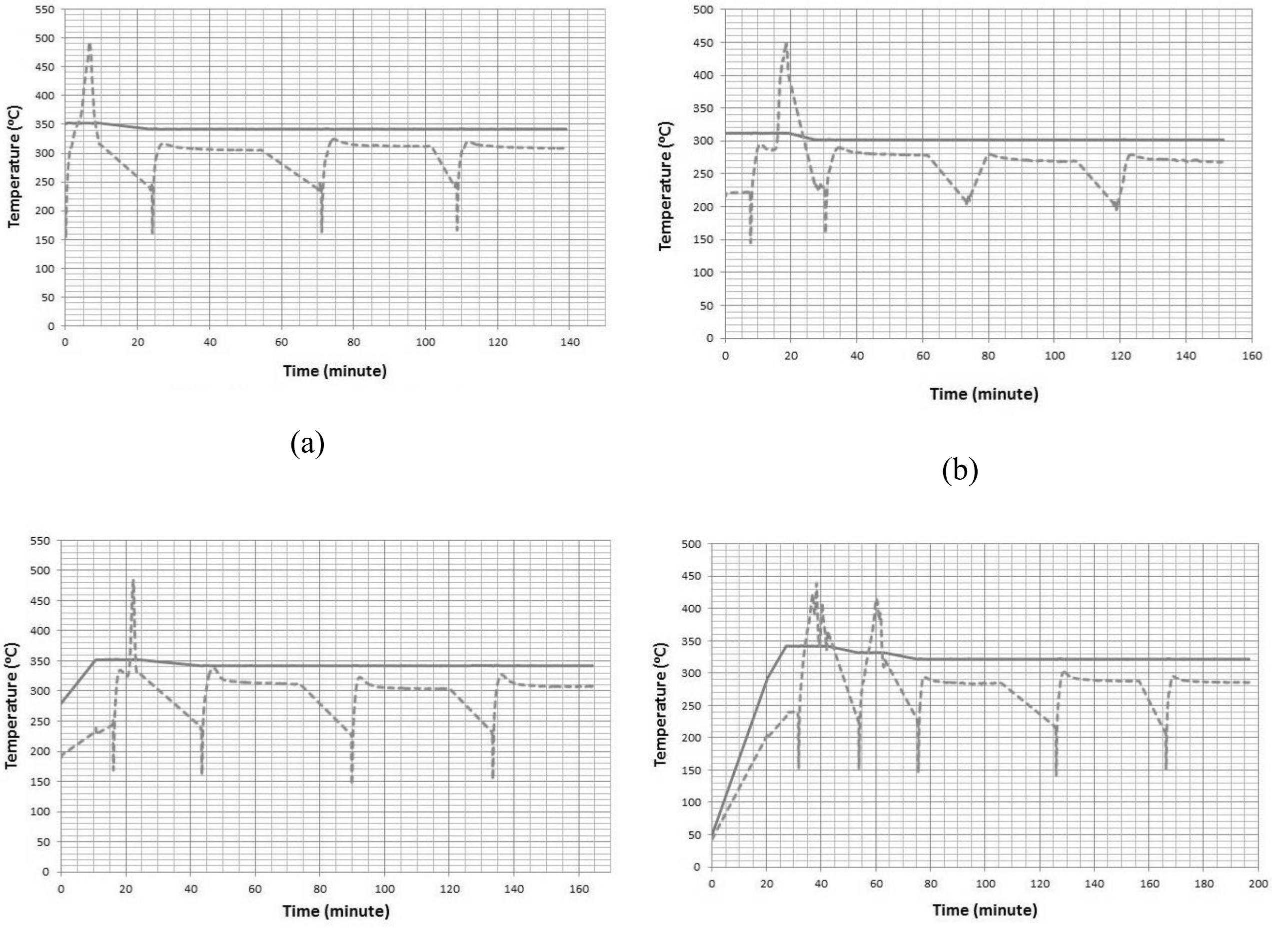


**Figure 2.** Self-ignition propensity risk ranking following the criteria in Ramírez et al.[7]

*3.5 Determination of Ignition Characteristics of Solid Biomass Dust Layer.*

The ignition characteristics of 5 mm thickness dust layers of the fuels and their blends were determined according to British Standard BS EN 50281-2-1. Typical temperature profiles are illustrated in Figures 3 and 4. This method involves heating a dust layer of known thickness on a hot surface for 30 min and noting firstly whether ignition happens or not within 30 min, and secondly how long it takes to occur. A fresh layer of dust is used for each temperature studied, and the temperature is sequentially reduced until there is no ignition. Here, heat transfer occurs from the hot surface through the dust layer to the surface layer which is exposed to the atmosphere. Thus, the temperature of the dust layer increases and exothermic chemical reaction begins. If the plate temperature is below a critical value, then the heat will dissipate at a faster rate than it is produced. Above a certain plate temperature (the critical temperature), the heat absorbed by the dust layer is unable to dissipate fast enough to the surroundings. At this point, the chemical reaction rate increases to an extent that the heat transfer to the surroundings happens too slowly to be able to compensate the heat generated from the increasing chemical reaction[14]. Thus, ignition of the dust layer happens. Ignition is indicated by both a rapid increase in surface dust layer temperature, as well as a visible glow.



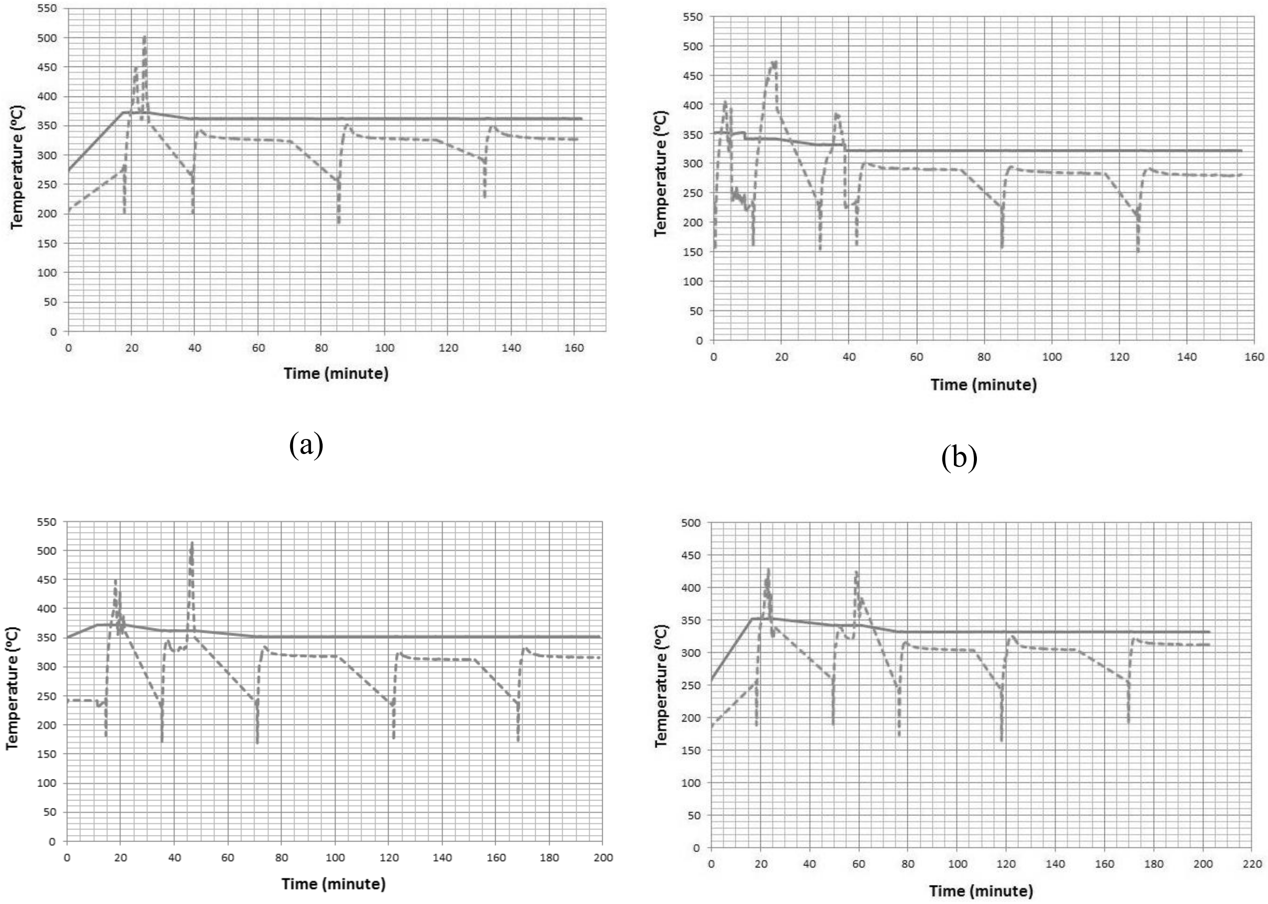
(a)

(b)

(c)

(d)

**Figure 3.** Heated plate (solid line) and dust layer (dashed lines) temperatures of: (a) untreated Pine – ignited at 350°C but not 340°C for three times; (b) untreated Miscanthus – ignited at 310°C but not 300°C for three times; (c) untreated PM9010 – ignited at 350°C but not 340°C for three times; (d) untreated PM5050 – ignited at 340°C, 330°C but not 320°C for three times.



(a)

(b)

(c)

(d)

**Figure 4.** Heated plate (solid line) and dust layer (dashed lines) temperatures of: (a) PineW1hr – ignited at 370ºC but not 360ºC for three times; (b) MiscW1hr – ignited at 350ºC, 340ºC and 330ºC but not 320ºC for three times; (c) PM9010W1hr – ignited at 370ºC, 360ºC but not 350ºC for three times, (d) PM5050W1hr – ignited at 350ºC, 340ºC but not 330ºC for three times

In this study, both the minimum ignition temperature and the corresponding ignition delay time were noted. Regardless of the material, ignition was accompanied by the appearance of clouds of yellowish-grey smoke. When the plate was just below the critical temperature and ignition failed to occur, a smaller quantity of greyish smoke was seen evolved early in the experiment signifying loss of moisture and volatiles from slow pyrolysis. The smoke intensity decreased throughout the experiment. In cases where the dust failed to ignite after 30 minutes, it was found that the dust layer near the hot surface had partially pyrolysed (slightly darker in color), but was unchanged at the surface, exposed to the atmosphere. There was a reaction gradient through the dust layer - the darkest color appeared closest to the heated plate and the color became lighter and lighter with increasing distance from the heated plate.

Referring to the temperature profiles in Figures 3 and 4, ignition is marked by a rapid increase in temperature at the dust layer surface, which exceeds the hot plate temperature. When the dust failed to ignite, there is a small exotherm on the surface dust temperature near the start of the experiment, but this drops to a stable temperature (lower than the hot plate temperature) which is maintained within the test duration. For cases when the dust failed to ignite, the experiment was repeated for another two times with fresh dust layers to confirm. The minimum ignition temperature of biomass dust layers and their blends are given in Table 5 together with the corresponding ignition delay times. There is an inverse relationship between minimum ignition temperature and ignition delay as seen by Jones et al.[8] in their study where low temperature ignition of biomass was the focus.

**Table 5.** Minimum Dust Layer Ignition Temperatures (in bold) and the Corresponding Ignition Delay Times and Some Results above the Minimum Dust Layer Temperatures

| **Material** | **Minimum Ignition Temperature ($^oC$)** | **Ignition Delay Time (min)** |
|---|---|---|
| **Pine** | **350** | **7.40** |
| **Misc** | **310** | **4.65** |
| **PM9010** | **350** | **5.47** |
| **PM5050** | 340 | 3.57 |
| | **330** | **5.90** |
| **PineW1hr** | **370** | **4.10** |
| **MiscW1hr** | 350 | 2.50 |
| | 340 | 2.72 |
| | **330** | **4.18** |
| **PM9010W1hr** | 370 | 2.82 |
| | **360** | **3.92** |
| **PM5050W1hr** | 350 | 3.60 |
| | **340** | **6.43** |

Consistent with the $T_{MWL}$ values obtained from the TGA/DTG measurements, pine is less reactive than miscanthus and there is a difference of 40$^o$C in the minimum ignition temperatures. The behavior of the 90:10 blend pine:miscanthus is dominated by the pine, and the minimum ignition temperature is the same as that of pure pine. However, there is a slight decrease in the minimum ignition temperature of the 50:50 blend, indicating that the more reactive miscanthus is causing the dust layer of the blend to be slightly more reactive too.

The impact of washing on dust layer ignition risk was more significant on individual fuels than on their blends. The minimum ignition temperature of both washed pine and washed miscanthus dust layers increased by 20°C compared to their untreated counterparts. However, this increase in minimum ignition temperature was less significant for the blends of washed fuels, regardless of the ratio. Dust layers from both the 9010 and 5050 blends of washed fuels showed only a 10°C increase in the minimum ignition temperature when compared to those of the untreated blends.

The impact on ignition delay time of washed biomass can also be observed in Table 5. Because of the inverse relationship between minimum ignition temperature and ignition delay, it is difficult to use ignition delay time as an indicator of ignition risk. However, if we compare cases where the minimum ignition temperatures of the dust layers were equal, we see some interesting observations: Comparing experiments at 350°C, dusts from pine alone have the lowest ignition risk, and blending with miscanthus (PM9010) reduces the ignition delay time by ~2 mins. Washed miscanthus has the shortest ignition delay time at this temperature and can therefore be considered much higher risk than pine.

The effect of blending is obvious when reactivity is viewed from the point of dust minimum ignition temperature. From the results, the minimum ignition temperatures for both individual pine and PM9010 were the same, i.e. 350°C; but when the hot surface was set to 345°C, pine alone failed to ignite but PM9010 ignited. With just an addition of 10wt% miscanthus that ignited at a lower temperature on its own had actually made the blend more reactive judging from the dust minimum ignition temperature viewpoint. Referring to the samples used in this study, it is clear that dust layers from a biomass mixture can be more reactive than dust layers from individual biomass. A small amount of blend component that ignited at a lower temperature would cause the overall blend to ignite at a lower temperature and that pretreatment by washing can make the dust layers less reactive by removing catalytic potassium. However, the results from these experiments are not significant enough to affect plant operations, providing dust layers on heated surfaces are thin. There are two relevant NFPA guidelines for the prevention of fires due to ignition of dust layers on hot surfaces: Recommended Practice for the Classification of Combustible Dust and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas (NFPA 499)[15], and Standards on the Fundamentals of Combustible Dust (NFPA 652)[16]. The former limits the surface temperature of heat-producing equipment to either the lower of the ignition temperature or 165°C (as organic dust on hot surfaces can dehydrate or carbonise over time resulting in lower ignition temperatures), whilst in the latter surface temperatures are recommended to be maintained at least 50°C below the dust layer and dust cloud ignition temperatures (as measured by standard methods). While differences are noticeable between the critical dust layer ignition temperature and different fuels, blends or pretreated fuels studied here, it should be noted that all of these temperatures fall in the range 310-370ºC, and according to the guidelines listed above would not be expected to impact on plant management in terms of house-keeping and dust management. Because of the inverse relationship between temperature and ignition delay, the small difference in behavior reported here, will become increasingly significant for thicker and thicker dust layers. Future work will consider modelling the heat transfer and examine the impact of dust layer thickness on minimum ignition temperatures and ignition delay. It is also worth examining whether the dust particle size will affect the dust layer minimum ignition temperatures and the corresponding ignition delay time.

## 4. CONCLUSIONS

This work is concerned with the risk for ignition of two biomass and their blends, pine and miscanthus. The reactivity of these two fuels and their blends (90:10 and 50:50 by weight of pine:miscanthus) was assessed by TGA and the temperature of maximum rate of weight loss and devolatilisation kinetics were used to assess the ignition risk. There is a difference in reactivity of these two fuels and miscanthus is more reactive but their risk ranking is similar (high risk). This technique also suggested that the blends, although still in the high risk category, are less reactive than the pure components.

The impact of pretreatment via water washing on reactivity and ignition risk was also assessed. Results indicated that catalytic metals ($K^+$ and $Ca^{2+}$) as well as chloride were removed by washing with good efficiencies for the miscanthus (90% K, 18% Ca removal percentages) compared with pine (38% K, 3% Ca). This resulted in less reactive fuels, particularly for miscanthus, but they were still categorized as high risk according to the TGA method. The ignition risk of 5 mm dust layers on a hot surface was also evaluated for dusts from pure biomass (untreated and washed) and from blends (untreated blends and washed blends). This involved finding the lowest temperature at which the dust ignited within 30 min. Miscanthus dust had the highest risk of dust ignition, with the lowest minimum temperature of ignition (310$^{o}$C) and the shortest ignition delay time at any given temperature. Dust layers of a 50:50 blend of pine and miscanthus ignited at a slightly lower (by 10$^{o}$C) temperature than pure pine, suggesting that the reaction of miscanthus causes ignition of the pine also. Dust layers from the washed pine and miscanthus had higher minimum ignition temperatures and therefore present a slightly lower risk. It is believed that the removal of K and Ca from the biomass upon washing is the main reason that changed the dust minimum ignition temperature. Nevertheless, all minimum dust layer temperatures are in the range 310-370$^{o}$C and these differences are not considered significant enough to affect plant operation with respect to monitoring/cleaning of thin dust layers. Current guidelines for the prevention of fires due to ignition of dust layers on hot surfaces as given by the NFPA limit the surface temperature of heat-producing equipment to either (at least) 50°C below the dust layer and dust cloud ignition temperatures (as measured by standard methods) or 165°C. Since the critical temperatures measured for the fuels studied (validated for dust layers up to 5 mm thickness) are considerably higher than the limit given (i.e. 165°C), our findings would not be expected to impact on plant management in terms of house-keeping and dust management. However, the minimum dust layer ignition temperatures decrease, and ignition delay times increase substantially with dust layer thickness so the small differences in self-ignition behavior reported here for blended and washed fuels will become more marked as dust layer thickness increases.

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## REFERENCES

(1) Chronicle Live Publication Firefighters Battle Biomass Blaze at Port of Tyne. http://www.chroniclelive.co.uk/news/firefighters-battle-biomass-blaze-port-6177485 (accessed 8 January 2014).

(2) Mortari, D. A.; Ávila, I.; Santos, A. M. d.; Crnkovic, P. M., Study of Thermal Decomposition and Ignition Temperature of Bagasse, Coal and Their Blends. *Engenharia Térmica (Thermal Engineering)* **2010,** *9*, 81-88.

(3) Wilén, C.; Moilanen, A.; Rautalin, A.; Torrent, J.; Conde, E.; Lödel, R.; Carlson, D.; Timmers, P.; Brehm, K. *Safe handling of renewable fuels and fuel mixtures*; VTT Technical Research Centre of Finland: Finland, 1999; pp 1-127.

(4) Saddawi, A.; Jones, J. M.; Williams, A.; Coeur, C. L., Commodity Fuels from Biomass through Pretreatment and Torrefaction: Effects of Mineral Content on Torrefied Fuel Characteristics and Quality. *Energy & Fuels* **2012,** *26*, 6466-6474.

(5) Deng, L.; Zhang, T.; Che, D., Effect of Water Washing on Fuel Properties, Pyrolysis and combustion Characteristics, and Ash Fusibility of Biomass. *Fuel Processing Technology* **2013,** *106*, 712-720.

(6) Hayhurst, A. N., The kinetics of the pyrolysis or devolatilisation of sewage sludge and other solid fuels. *Combustion and Flame* **2013,** *160*, 138-144.

(7) Ramírez, A.; García-Torrent, J.; Tascón, A., Experimental Determination of Self-Heating and Self-Ignition Risks Associated with the Dusts of Agricultural Materials Commonly Stored in Silos. *Journal of Hazardous Materials* **2010,** *175*, 920-927.

(8) Jones, J. M.; Saddawi, A.; Dooley, B.; Mitchell, E. J. S.; Werner, J.; Waldron, D. J.; Weatherstone, S.; Williams, A., Low temperature ignition of biomass. *Fuel Processing Technology* **2015,** *134*, 372-377.

(9) Saddawi, A.; Jones, J. M.; Williams, A.; Wójtowicz, M. A., Kinetics of the Thermal Decomposition of Biomass. *Energy & Fuels* **2010,** *24*, 1274-1282.

(10) Friedl, A.; Padouvas, E.; Rotter, H.; Varmuza, K., Prediction of heating values of biomass fuel from elemental composition. *Analytica Chimica Acta 2005* **2005,** *544*, 191-198.

(11) Bridgeman, T. G.; Jones, J. M.; Williams, A.; Waldron, D. J., An investigation of the grindability of two torrefied energy crops. *Fuel* **2010,** *89*, 3911-3918.

(12) Nowakowski, D. J.; Jones, J. M.; Brydson, R. M. D.; Ross, A. B., Potassium catalysis in the pyrolysis behavior of short rotation willow coppice. *Fuel* **2007,** *86*, 2389-2402.

(13) Fahmi, R.; Bridgwater, A. V.; Darvell, L. I.; Jones, J. M.; Yates, N.; Thain, S.; Donnison, I. S., The effect of alkali metals on combustion and pyrolysis of Lolium and Festuca grasses, switchgrass and willow. *Fuel* **2007,** *86*, 1560-1569.

(14) Pastier, M.; Tureková, M. I.; Turňová, Z.; Harangozó, J., Minimum Ignition Temperature of Wood Dust Layers. *Research Papers Faculty of Materials Science and Technology in Trnava* **2013,** *Special Number*, 127-131.

(15) NFPA Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Area. http://inferno4.spffa.com/pdf/nfpacodes/nfpa_499.pdf (accessed 20 October 2015).

(16) NFPA Preliminary First Draft Proposed 2015 Edition NFPA 652. https://www.nfpa.org/Assets/files/AboutTheCodes/652/652_PreliminaryDraft.pdf (accessed 20 October 2015).