An investigation of the grindability of two torrefied energy crops

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Abstract

The process of torrefaction alters the physical properties of biomass, reducing its fibrous tenacious nature. This could allow increased rates of co-milling and therefore co-firing in coal fired power stations, which in turn would enable a reduction in the amount of coal used and an increase in the use of sustainable fuels, without the need for additional plant. This paper presents an experimental investigation of the pulverisation behaviour of two torrefied energy crops, namely: willow and Miscanthus. A multifactorial method approach was adopted to investigate the three process parameters of temperature, residence time and particle size, producing fuels treated using four different torrefaction conditions. The untreated and torrefied fuels were subjected to standard fuel analysis techniques including ultimate analysis, proximate analysis and calorific value determination. The grindability of these fuels was then determined using a laboratory ball mill and by adapting the Hardgrove Grindability Index (HGI) test for hard coals. After grinding, two sets of results were obtained. Firstly a determination similar to the HGI test was made, measuring the proportion of sample passing through a 75 µm sieve and plotting this on a calibrated HGI chart determined using four standard reference coals of known HGI values. Secondly the particle size distributions of the entire ground sample were measured and compared with the four standard reference coals. The standard fuel tests revealed that temperature was the most significant parameter in terms of mass loss, changes in elemental composition and energy content increase. The first grindability test results found that the untreated fuels and fuels treated at low temperatures showed very poor grindability behaviour. However, more severe torrefaction conditions caused the fuels to exhibit similar pulverisation properties as coals with low HGI values. Miscanthus was found to have a higher HGI value than willow. On examining the particle size distributions it was found that the particle size distributions of torrefied Miscanthus differed significantly from the untreated biomass and had comparable profiles to those of the standard reference coals with which they had similar HGI values. However, only the torrefied willow produced at the most severe conditions investigated exhibited this behaviour, and the HGI of torrefied willow was not generally a reliable indicator of grindability performance for this energy crop. Overall it was concluded that torrefied biomass can be successfully pulverised and that torrefied Miscanthus was easier to grind than torrefied willow.

Keywords: biomass, energy crops, torrefaction, thermal pre-treatment, grindability.

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1. Introduction

Bioenergy and biomass fuels are seen by many as making an important contribution to low carbon energy generation and transport fuels in the short to medium term [1]. The thermal pre-treatment of biomass fuels, or torrefaction, has received an increasing amount of interest in recent years [2, 3]. Torrefaction improves the solid fuel properties of biomass. It is a mild temperature pyrolysis process that removes moisture and a proportion of the volatile content and leaves a dry, partially carbonised solid. This increases the energy density in the fuel on a mass basis, and - after pelletisation - on a volume basis too; torrefied pellets can have energy densities approaching those of coal [4]. Torrefaction can also be considered a high temperature drying stage, and it performs two functions: removing the moisture (and low molecular weight volatile compounds) from the fuel, and creating a hydrophobic solid that reabsorbs only small amounts of moisture [5]. Combined with chemical changes in the solid, this treatment reduces the microbial activity [6], which presents a number of storage benefits. Finally, the fuel undergoes physical changes, increasing its brittle nature and reducing the tenacity of the polymeric fibres present in woody and herbaceous biomass species [6, 7]. This suggests that grindability of the fuel increases and it is likely that biomass can be milled with coal at increased co-milling rates.

In the UK, the majority of coal fired power stations are co-firing biomass. In 2008, 1.6 TWh of electricity was produced from co-firing domestic and imported biomass with coal, and this accounted for 9 % of total renewable energy generation [8] (The total generation from coal was 125 TWh, and therefore the total UK co-firing rate was 1.3%). However, co-firing of biomass is not without problems. The addition of biomass quickly reduces the mill capacity during fuel handling due to the fibrous nature of some feedstocks. Higher throughputs can be achieved with dedicated co-fired schemes. However, co-milling and firing is attractive compared to a co-fired scheme, which requires a separate biomass feed system to act in parallel with the coal feed system, and also avoids additional maintenance and installation costs. One of the problems with burning biomass is the difficulty in reducing it to an acceptable practical size for transportation and combustion within the furnace. This is especially true for energy crop fuels, which are characterised by their fibrous nature and high moisture content. Thus there is a large strategic need for technologies that can increase the throughput of biomass in coal handling facilities.

The milling of coal for pulverised fuel boilers is a matter of significant importance. The particle size distribution affects important parameters such as the combustion efficiency, the amount of unburnt

carbon in the ash, and the stability of combustion. In addition the operation efficiency of the pulverising unit is critical to the successful reduction of NOx emissions in boilers retrofitted with low NOx burners [10]. A pulveriser system refers to the drying, grinding, classification (sizing) and transportation of the fuel to the burner. Each of these stages is influenced by the physical properties of the fuel, which are in turn dependant on the composition of the fuels. These properties can limit mill throughput and therefore the boiler loading [11].

The most common grindability test for coals is the Hardgrove Grindability Index (HGI) [12], which is used to predict the capacity, performance and energy requirement of the mill as well as the typical particle size distribution after milling. It has become the most important commercially and is used in coal contract specification. However, the test does suffer from some limitations. For example, the measurement can be insensitive to the heterogeneous properties of coal that arise from different mineral contents, maceral constituents and levels of maturity [13]. The test, as described in the British Standard BS 1016-112:1995 [14], involves grinding 50 g of air dried coal with a fixed particle size distribution between 600 µm and 1.18 mm for 60 revolutions in a purpose built Hardgrove grindability machine. The proportion of sample then passing through a 75 µm sieve is then measured. Firstly, a calibration curve is plotted using four standard references samples of known HGI values. Once this is obtained, the proportion of the sample material passing through a 75 µm sieve is measured and plotted on the calibration curve, from which the HGI is determined. As a general rule, higher HGI values mean that the fuel is easier to grind, requiring lower power inputs and giving higher throughputs of fuel in the mill and through to the boiler.

There has been some work in the literature which suggests that the power consumption for milling woody biomass decreases after undergoing a thermal pre-treatment process, and that more uniform particle shape results [7, 15]. These studies have been conducted using cutting mills, suitable for untreated biomass but which are unable to assess the pulverisation of torrefied fuels. Therefore, it is difficult to assess the performance and potential of co-milling using these results. Bergman et al [8] did conduct preliminary investigations into the Hardgrove Grindability Analysis of torrefied fuels, but preferred instead to use a cutting mill to measure energy input required to grind biomass and the HGI assessments were not comprehensive. There has yet to be published a detailed study on the performance of size reduction by pulverisation of torrefied biomass. Work reported here, aims to examine this using an adapted version of the HGI, a description of which can be found in the experimental section.

2. Experimental

2.1. Torrefaction procedure

The torrefaction tests used a three zone horizontal tube furnace with an internal diameter of 75 mm and 750 mm long. The three zone design allows for maximum temperature control, and a larger total heated length of approximately 575 mm. The reactor tube is 800 mm in length and has an internal diameter of 60 mm. This allows for up to approximately 100 g of sample to be treated upon each batch run. A schematic diagram of the apparatus used is shown in Figure 1. The three thermocouples are placed at 20 cm intervals inside the length of the reactor tube, providing a temperature profile within the reactor tube during the process. These allow measurement of the inert gas temperature before the sample (T1 and T2) whilst the third thermocouple (T3) provides data on the temperature within the sample. Nitrogen is supplied to the reactor from a gas cylinder and controlled using a valve and flowmeter

Whilst there are a number of variables to consider during torrefaction, the two most critical to the process - in terms of both the conversion of the fuel and the economic constraints - are temperature and residence time. Particle size is also influential and is the third parameter investigated in this study. The process variables have been investigated with a factorial method using a three factor methodology. This is the most efficient approach to reveal the manner in which the selected variables of temperature (T), time (t) and particle size (d) influence the process. A typical approach to the results is shown in Table 1 [16]. This multifactorial design involves changing two factors in each run. For example, experiments are conducted at high temperature with small residence time and small particle size, and then with long residence time and large particles. The two chipped fuels had different average particle sizes and so for willow the small and large particle sizes were selected as <10 mm and >20 mm. For Miscanthus the two particle sizes were <4 mm and >10 mm. The fines (<1mm) are removed from the smallest particle sizes of both fuels.

Averaged results of the three factor design are calculated as:

$$\text{Low } T_{average} = (B+C)/2; \quad (1)$$

$$\text{Low } t_{average} = (A+C)/2; \quad (2)$$

$$\text{Low } d_{average} = (C+D)/2; \quad (3)$$

$$\text{High } T_{average} = (A+D)/2; \quad (4)$$

$$\text{High } t_{average} = (B+D)/2; \quad (5)$$

$$\text{High } d_{average} = (C+D)/2. \quad (6)$$

These are then used to calculate the influence of temperature, residence time and particle size as follows:

$$\Delta T = \text{High } T_{average} - \text{Low } T_{average} \quad (7)$$

$$\Delta t = \text{High } t_{average} - \text{Low } t_{average} \quad (8)$$

$$\Delta d = \text{High } d_{average} - \text{Low } d_{average} \quad (9)$$

If the high $T_{average}$ result varies significantly from the low $T_{average}$ result, then it follows that the temperature factor has produced this difference. This method allows for the role of three factors at two levels to be ascertained in only four tests. It also determines the interdependence of the variables.

The treated fuels were labelled according to the variable conditions of the treatment, as indicated by the response column in Table 1. For example, 'Willow A' will refer to the willow <10 mm sample that has been thermally treated at 290 °C for a reaction time of 10 mins. Images of the treated fuels are shown in Figure 2.

2.2. Fuel Analysis

The feedstock energy crops (combined particle sizes) studied were willow (short rotation coppice) and Miscanthus – both supplied by Rothamsted Research, Harpenden, UK. They have been analysed using standard fuel tests: proximate, ultimate and calorific value (calculated from CHN contents). The proximate analysis were conducted according to the methods laid out in standards CEN/TS 14775:2004 (moisture), CEN/TS 14774-1-3:2004 (volatiles) and CEN/TS 15148:2005 (ash), whilst the ultimate analysis was performed using a CE Instruments Flash EA 1112 Series elemental analyzer. The fuels are ground to <1mm in accordance with the test requirements.

The calorific value was calculated from a formula derived by Friedl et al [17]:

$$HHV = 3.55C^2 - 232C - 2230H + 51.2C \times H + 131N + 20{,}600 \quad (10)$$

Where HHV is in kJ/kg and C, H, N, are mass% on a dry basis. The model gives a standard error of calibration of 337 kJ kg^{-1} and a R^2 of 0.943 based on analysing a number of biomass fuels. The high C content of the thermally pre-treated fuels may lead to inaccuracies in using this correlation (10) and therefore calorific values of a number of the thermally pre-treated fuels have been determined using Bomb Calorimetry analysis to validate the calculated values.

2.3. Energy Yields

The energy yields are a useful measure of the process and are calculated from the mass yields, as described by Bergman et al [18]. The mass yield, η_m, and energy yield, η_E, calculations are shown in equations (11) and (12) below, where $m_{treated}$ = mass of treated fuel, m_{raw} = mass of untreated fuel, HHV= high heating value:

Mass Yield: $$\eta_m = \frac{m_{treated}}{m_{raw}} \times 100 \quad (11)$$

Energy Yield: $$\eta_E = \eta_m \times \frac{HHV_{treated}}{HHV_{raw}} \times 100 \quad (12)$$

2.4. Thermal Pre-treated Fuel Grindability Index:

In the standard method for HGI (50 g fuel) the volumes of biomass and coal will differ significantly yet receive the same amount of grinding energy in the mill. As pointed out by Joshi [19] and Agus and Waters [20], this favours dense coals with smaller volume and, therefore, is unsatisfactory for making direct comparisons between the two fuels. To correct this situation, the HGI test has been modified as suggested by Joshi and Agus and Waters, and grindability has been determined by using the same fixed volume (50 cm^3) for each coal and biomass sample as opposed to a fixed mass (50 g).

The grinding of the fuels was accomplished using a Retsch PM100 ball mill. Preliminary milling tests were conducted using coal, biomass and thermally pre-treated biomass in order to determine the optimum operating conditions for the torrefied material. The mill was then calibrated with coal in order to allow a comparison between the fuels to be made. The results from this testing have led to the following procedure:

2.4.1 Volumetric HGI test

Calibration of Mill

1. Approximately 1kg of a standard reference coal with known HGI is ground using a Retsch cutting mill SM 100, using a 4 mm screen.
2. The sample is then sieved using 1.18 mm and 600 µm size sieves.
3. 50 cm^3 of each sample is then measured out and weighed using a measuring cylinder with an accuracy of ±0.1 cm^3 and a balance accurate to ±0.01g.
4. The 50 cm^3 sample is then placed into a 250 ml capacity stainless steel milling cup with 15 × 20mm stainless steel balls and ground for 2 minutes at 165 rpm.
5. The sample is then removed from the grinding cup and separated using a 75 µm sieve and a sieve shaker (5 mins). The two separate fractions are weighed to the nearest 0.01 g. If there is a loss of sample greater than 0.5 g the test is aborted and repeated.
6. The mass in grams passing through the 75 µm sieve is calculated using:

$$m = m_v - m_1 \quad (13)$$

where m_v = mass of 50 cm^3 of sample

m_1 = mass of sample collected on 75 µm sieve.

7. The process is repeated three more times and an average value from the four results calculated.
8. The process is repeated for the three other coals. (For this project four coals of HGI values of 35, 49, 66 and 92 were used.)
9. The results are used to plot a calibration curve for the mill of **HGI** versus **m**.

Testing of biomass fuel

1. Steps 1-6 above were repeated for all feedstocks and thermally pre-treated fuels, with results produced in duplicate.
2. The results are then plotted on the calibration curve and a HGI value is assigned to the biomass fuels.

2.4.2 Particle Size Distribution Profiles

To provide a more thorough assessment of the grindability behaviour of the thermally pre-treated fuel in comparison to coal, a particle size distribution of the ground fuels was also conducted. This involved the same grinding process described in steps 1 to 4 above but subsequent to this process, the fuels were sieved with a series of sieves of mesh sizes 600, 355, 212, 150, 75 and 53 µm. The mass of each sample collected on each sieve was measured and recorded as a percentage of the

original sample mass. A plot of the particle size distribution of each ground sample was made using an average particle size of the sample collected on each sieve as the midpoint between two consecutive sieve sizes (e.g. the mid point value/average particle size of sample collected on the 355μm sieve was assumed to be 477.5 μm). The particle sizes of thermally treated biomass were plotted alongside those of the four HGI standard reference coals to compare their behaviour.

3. Results and Discussion

3.1. Fuel Characterisation

The mass yields for the test matrix of the torrefied fuels are shown in Table 2. Miscanthus mass yields are lower than those of willow, and this effect is increased at higher temperature treatment. The main reason for the difference between the two fuels is believed to be primarily due to differences in the hemicellulose content [8].

The multifactorial method calculations for mass yields are shown in Table 3 and demonstrate the different influence of the three parameters. The order of significance of the parameters was found to be:

Temperature > Reaction time > Particle size

The difference between the high temperature and low temperature mass loss averages was 19.4 % and 24.0 % for willow and Miscanthus respectively. Varying the residence time between short and long caused average mass losses of approximately half that seen for temperature. Although less significant, residence time is still an important parameter of the process. Finally, the average mass loss difference between large and small particles was 3.2 % and 2.9 % for willow and Miscanthus. Although there is a small difference, close to the errors of the measurement, it possibly suggests that larger particles undergo greater mass loss.

Proximate analysis results are given in Table 4. The trend is of decreasing volatile content and increasing fixed carbon content as the temperature and residence time of the process increases. The moisture contents of the torrefied fuels suggest that a small amount moisture is reabsorbed during storage. This re-absorption appears to be unrelated to the temperature at which the fuels were treated.

Elemental analysis of the pre-treated fuels (Table 5) demonstrates the effect of thermal treatment on increasing the carbon content and decreasing the oxygen content. One result of this is an increase in energy content of the fuels. Table 5 shows the calculated HHV values for all the fuels. For the pre-treated fuels with carbon contents greater that 50.5 % on a dry basis – the upper limited of the fuels tested by Friedl et al [17] – the HHVs were measured by bomb calorimetry. The measured results are comparable with those calculated with the differences ranging from 300 – 700 kJ kg^{-1}. (Although the biggest difference between the measured and calculated results was for the torrefied Miscanthus with the highest carbon content, the differences did generally not increase for higher carbon contents.)

The ultimate analysis showed that thermal pre-treatment caused a small reduction in hydrogen content in the fuels. Nitrogen was undetected in the Miscanthus samples, but the willow results suggest that thermal pre-treatment causes a slight increase in the nitrogen content of the fuels.

The ultimate analysis results have been used to plot the atomic ratios of oxygen to carbon and hydrogen to carbon on a Van Krevelen plot, alongside a number of other solid fuels including various coals and charcoal. This plot is shown in Figure 3. The diagram shows the influence of thermal pre-treatment conditions on the properties of biomass, shifting them away from biomass and towards coal. The willow and Miscanthus torrefied fuels produced from the high temperature and long residence time conditions have atomic elemental ratios comparable to lignite.

3.2. Grindability Test

The four HGI standard reference coals were successfully ground in the mill using the conditions established in Section 2.4. The calibration graph for the four coals of HGI values of 35, 49, 66 and 92 is shown in Figure 4. The R^2 value for the correlation was 0.97.

This graph was used to calculate and assign equivalent HGI values for the *m* values obtained after pulverising the feedstocks and torrefied fuels, using equation (14):

$$HGI_{equiv} = \frac{(m - 0.9856)}{0.1575} \qquad (14)$$

These results are shown in Table 7. It can be seen that the raw feedstocks behaved poorly in these grinding conditions with 0.5 % of willow and 0.1 % of Miscanthus passing through the 75 µm sieve. This equated to a HGI value of 0 for both crops. For a low temperature and short residence time treatment, fuels exhibited no change in their physical properties as measured by this test. After a longer residence time at 240 °C there is some change in the grindability of the fuels, but it is only after treatment at 290 °C that noteworthy changes occur. A combination of long residence time and high temperature was required to produce thermally pre-treated fuels with similar grinding properties to the reference coals. Willow D was found to have an equivalent HGI value of 51, whilst Miscanthus D was measured as having an equivalent HGI value of 79.

Table 8 shows the multifactorial calculations of the measured grindability index. The influence of the different parameters again follows the order seen in mass loss with temperature being the most significant, followed by residence time and then particle size. However, it was observed that whilst different particle sizes in the willow feedstock had a minimal impact, the different particle sizes investigated for Miscanthus had a significant variance in their grindability behaviour.

Whilst this method appears to be successful in determining the changes in grindability of the fuels after pre-treatment, it is also has some limitations. Firstly, it would appear simplistic to conclude that willow treated at 290 °C for 60 minutes inherits the physical properties of a hard coal with a low HGI. Furthermore, the standard HGI test requires that the majority of the sample to be tested is in the 1.18mm – 600µm particle size range. However, for some of the pre-treated biomass the amount of sample in this size range was less than 50% as most was ground to <600 µm in the preliminary milling stage. Therefore the result may not represent the entire sample. However, this suggests that the results may underestimate the grindability of torrefied fuels.

3.2.1 Particle size distribution

The particle size distribution of the entire ground sample after pulverisation was assessed to gather further information of the behaviour of the fuels. The coals were first analysed to provide data on the particle size distribution of standard reference coals of known HGI values. This data is presented in Figure 5 and shows that a larger proportion of finer gradings are obtained from softer coals.

The particle size distributions of the four different willow tests together with the four HGI coals are provided in Figure 6(a). It can be observed that as treatment occurred at high temperatures and for

longer residence times, grinding became progressively easier. However, the particle size distribution profiles are different to those of coals ground under the same conditions, and there are different proportions of particle size fractions within the ground samples. For example, although a similar proportion of the willow A sample passed through 75 µm as a coal with an HGI value of 35, the remainder of the sample has a higher proportion of large particles. The exception is willow D that was calculated as having an equivalent HGI of 51, and appears to have a particle size distribution profile that fits between coals with an HGI value of 49 and 66.

Figure 6(b) shows the same plot for the untreated and thermally treated Miscanthus. The profile for the untreated sample demonstrated how only a small fraction of this sample was reduced in particle size. However, the four thermally pre-treated fuels all show a significant change in particle size distribution profiles, even at the lowest conditions investigated. Furthermore, all of these profiles are similar to the four coals. The particle size distribution of ground Miscanthus A with a calculated HGI value of 26, has a similar profile to coal with an HGI of 35, and Miscanthus D with a calculated HGI value of 79 has a comparable profile to the coals with HGI values of 66 and 92. Therefore under the same processing conditions as willow, Miscanthus should be easier to grind.

One practical use of the HGI is as a prediction for the particle size distribution of different coals. The results show that it is not suitable to make this correlation for willow fuels. However, the results suggest that this prediction may be more reliable for Miscanthus.

4. Conclusions

The work has shown that temperature is the most important parameter in terms of mass loss, increase in carbon content (and energy content) and in ease of grindability of the solid product. In simpler terms, temperature is critical in the conversion of biomass to a satisfactorily pre-treated solid fuel. However, it has also been demonstrated that residence time plays an important role in the conversion of the fuel, particularly in the increase in carbon content and the ease of grindability of the fuel.

Pulverisation of the thermally pre-treated fuels was investigated by adapting the standard HGI test for coals and using a ball mill. The initial test assigned each fuel with an equivalent HGI value. Untreated biomass was difficult to pulverise, but thermal pre-treatment changed the physical properties of biomass to enable successful size reduction using this process. Miscanthus was easier to

grind: Willow D (> 20 mm, 290^{o}C for 60 min) was calculated as having a grindability index of 51, whilst Miscanthus D (>10 mm, 290 ^{o}C for 60 min) had an index of 79. The grindability of the fuels were assessed further by measuring the particle size distribution after pulverisation and compared to four standard reference coals. The results once again demonstrated how Miscanthus was easier to pulverise than willow, and the particle size distribution profiles of pulverised pre-treated Miscanthus were similar to those of coals with which they had similar equivalent HGI values. However, willow behaved differently, and this was only observed for willow treated at the highest temperature and for the longest time.

From the grindability results, it is concluded that willow requires high temperatures and longer residence times in order to obtain grindability behaviour similar to coal. In order to produce similar physical changes in Miscanthus, treatment at temperatures around 290 °C are also required but considerably shorter residence times are necessary. As a result of these results and observations, the authors believe that particle size distribution is a more satisfactory analysis of grinding behaviour than the Equivalent Hardgrove Grindability Index designed in this work.

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TABLES:

Table 1 Three factor design approach to the experimental work

Temperature T (°C)	Residence Time t (mins)	Particle Size d (mm)	Response (Mass yield / carbon content / grindability index)
High (290)	Short (10 mins)	Small (<10mm; <4mm)	A
Low (230-250)	Long (60 mins)	Small (<10mm; <4mm)	B
Low (230-250)	Short (10 mins)	Large (>20mm; >10mm)	C
High (290)	Long (60 mins)	Large (>20mm; >10mm)	D

Table 2 Mass yield results (dry basis)

Sample	T (°C)	t (min)	d (mm)	Mass yield (%)	
				Willow	Miscanthus
A	290	10	Small	81.6	75.7
B	240	60	Small	89.5	87.2
C	240	10	Large	97.7	96.9
D	290	60	Large	66.9	60.3

Table 3 Multifactorial method results of mass yields of both feedstocks after thermal pre-treatment experiments (according to equations (1) to (9)).

	Mass yield (%)	
	Willow	Miscanthus
High T average	74.3	68.0
High t average	78.2	73.8
High d average	82.3	78.6
Low T average	93.6	92.1
Low t average	89.7	86.3
Low d average	85.6	81.5
ΔT	-19.4	-24.0
Δt	-11.4	-12.5
Δd	-3.2	-2.9

Table 4 Proximate analysis of feedstock and torrefied fuels (as received)

	Moisture Content %	Volatile Content %	Fixed Carbon %	Ash Content %
Willow <10mm	8.9	74.5	14.8	1.8
Willow >20mm	8.9	74.1	15.5	1.5
Willow A	2.2	72.4	23.3	2.1
Willow B	2.1	75.8	20.6	1.5
Willow C	2.8	81.4	14.6	1.2
Willow D	2.1	66.9	29.2	1.8
Miscanthus <4mm	7.4	78.4	12.9	1.3
Miscanthus >10mm	7.0	77.8	14.0	1.2
Miscanthus A	2.2	63.8	32.6	1.4
Miscanthus B	2.3	76.4	20.0	1.3
Miscanthus C	2.5	81.3	15.0	1.2
Miscanthus D	2.6	60.0	35.5	1.9

Table 5 Ultimate analysis of feedstock and torrefied fuels (daf basis)

	C	H	N	S	O*	HHV kJ kg^{-1} (dry)	
						calculated	measured
Willow <10mm	48.6	6.4	0.58	0.00	44.4	19000	-
Willow >20mm	49.3	6.3	0.58	0.00	43.8	19300	-
Willow A	56.5	6.2	0.83	0.00	36.5	22400	21800
Willow B	54.3	6.0	0.76	0.00	38.9	21400	21000
Willow C	51.9	6.3	0.36	0.00	41.4	20500	-
Willow D	60.3	5.8	0.52	0.00	33.4	23900	23600
Miscanthus <4mm	49.3	6.4	0.00	0.00	44.3	19300	-
Miscanthus >10mm	48.5	5.9	0.00	0.00	45.6	18900	-
Miscanthus A	55.8	5.8	0.00	0.00	38.4	21900	21600
Miscanthus B	53.7	6.0	0.00	0.00	40.3	21100	20600
Miscanthus C	50.6	6.0	0.00	0.00	43.4	19800	-
Miscanthus D	63.4	5.7	0.00	0.00	30.9	25200	24500

* - calculated by difference

Table 6 **Energy yields of torrefied fuels**

Treatment	Willow	Miscanthus
A	89.9	81.0
B	95.0	89.9
C	96.8	96.4
D	77.6	76.0

Table 7 **Calculated theoretical HGI values of biomass fuels (from calibration curve)**

Run No.	T (°C)	t (min)	d (mm)	willow		Miscanthus	
				m (%)	HGI_{equiv}	m (%)	HGI_{equiv}
-	untreated	-	-	0.5	**0**	0.1	**0**
A	290	10	Small	4.7	**24**	5.1	**26**
B	240	60	Small	1	**0**	1.2	**1**
C	240	10	Large	2.6	**10**	2.8	**11**
D	290	60	Large	9.1*	**51***	13.4*	**79***

*** - single result, not duplicated**

Table 8 **Multifactorial method results of grindability index results of both biomass after torrefaction experiments**

	Grindability Index	
	Willow	Miscanthus
High T average	38	53
High t average	31	45
High d average	26	40
Low T average	5	6
Low t average	12	14
Low d average	17	19
ΔT	32	47
Δt	19	32
Δd	9	22

FIGURES:

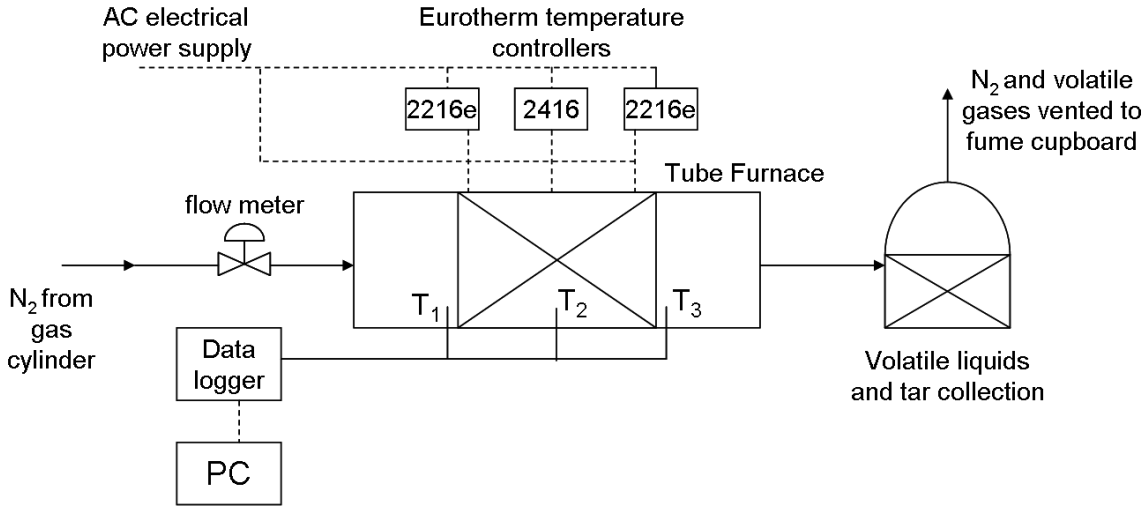

Figure 1 PID diagram of borosilicate reactor tube to thermally treat fuels.

Figure 2 Images of a) untreated willow; b) willow C; c) willow B; d) willow A; e) willow D. f) untreated Miscanthus; g) Miscanthus C; h) Miscanthus B; i) Miscanthus A; j) Miscanthus D.

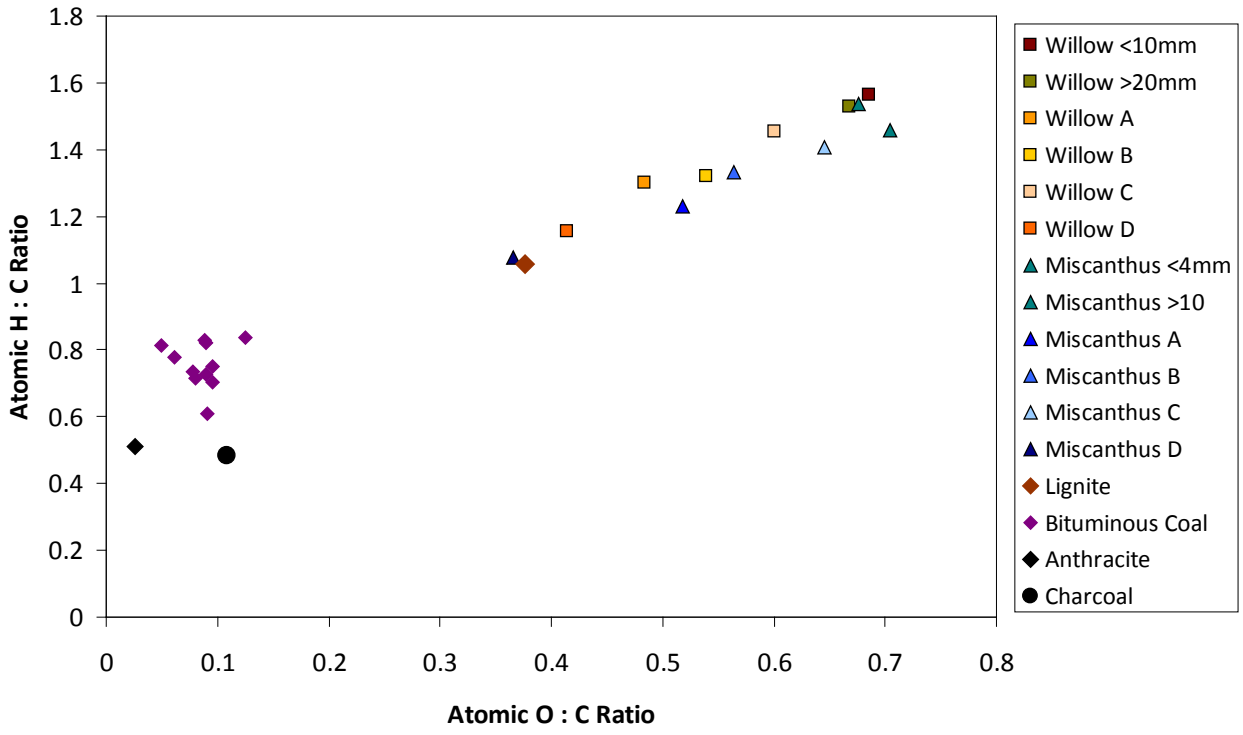

Figure 3 Van Krevelen Diagram showing properties of feedstock and thermally pre-treated fuels alongside a selection of other solid fuels

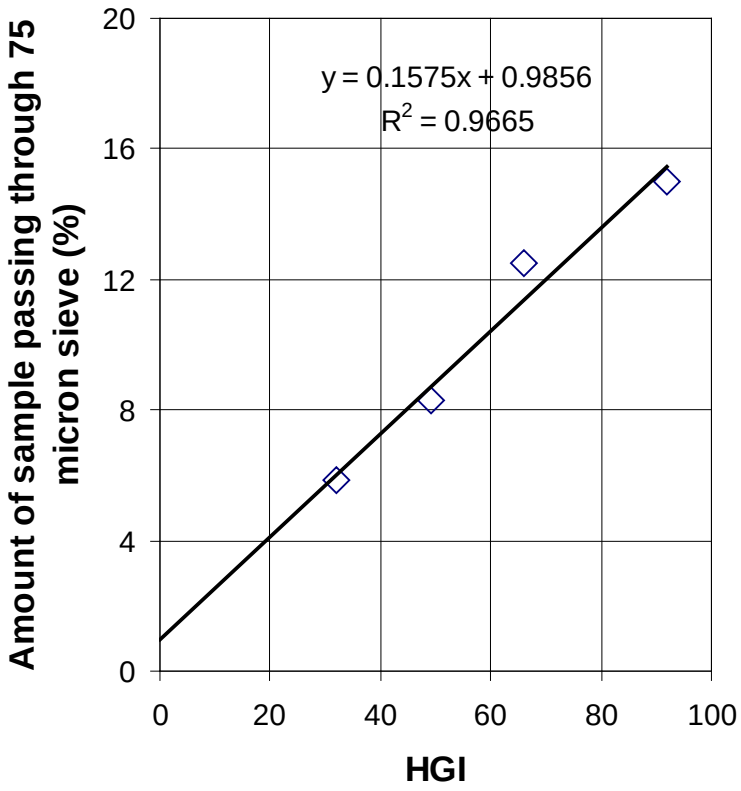

Figure 4 Calibration curve from four standard reference coals of HGI 32, 49, 66 and 92 for a Retsch PM100 ball mill

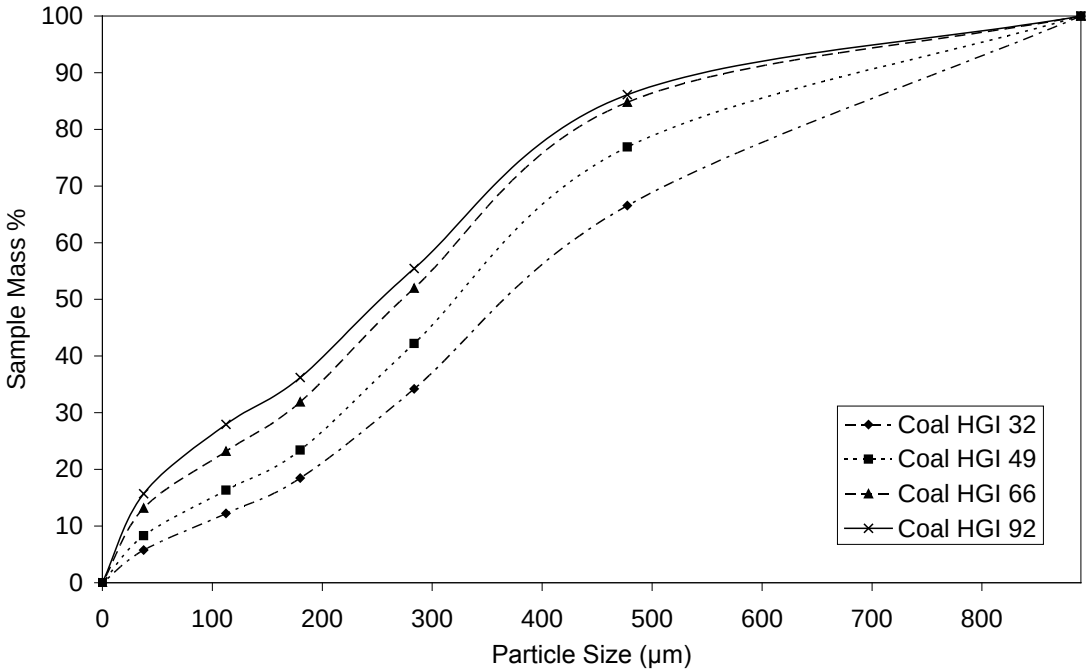

Figure 5 Particle size distribution curves for four standard reference coals of HGI 32, 49, 66 and 92

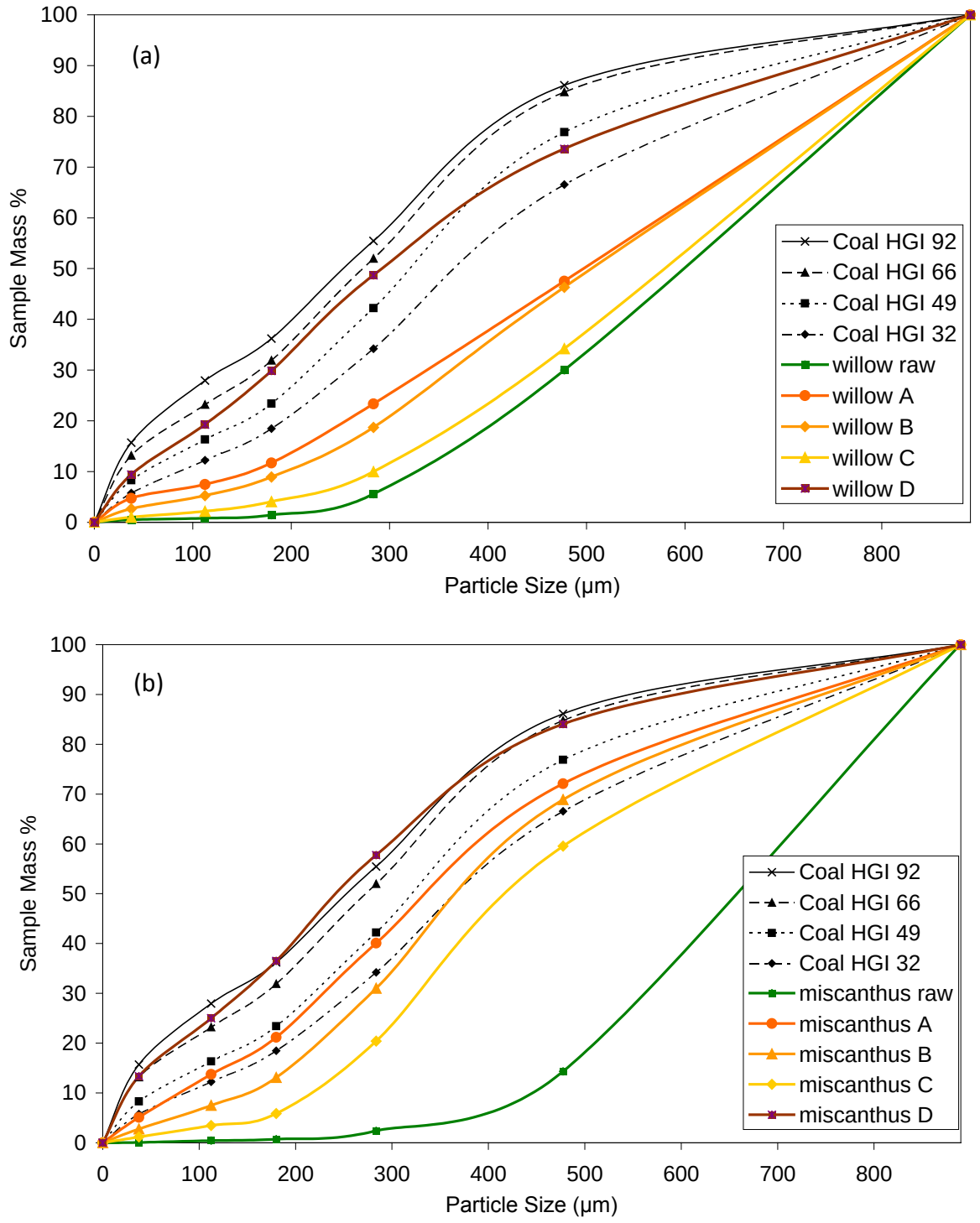

Figure 6 (a) Particle size distribution curves for untreated and torrefied willow alongside four standard reference coals of HGI 32, 49, 66 and 92. (b) Particle size distribution curves for untreated and torrefied Miscanthus alongside four standard reference coals of HGI 32, 49, 66 and 92