# PHYSICAL PRETREATMENT OF BIOGENIC-RICH TROMMEL FINES FOR FAST PYROLYSIS

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ABSTRACT: Energy from Waste (EfW) technologies such as fluidized bed fast pyrolysis, are beneficial for both energy generation and waste management. Such technologies however, face significant challenges due to the heterogeneous nature, particularly the high ash contents, of some municipal solid waste types e.g. trommel fines. A study of the physical/mechanical and thermal characteristics of these complex wastes is important for two main reasons; a) to inform the design and operation of pyrolysis systems to handle the characteristics of such waste; b) to control/modify the characteristics of the waste to fit with existing EFW technologies via appropriate feedstock preparation methods. In this study, the preparation and detailed characterization of a sample of biogenic-rich trommel fines has been carried out with a view to making the feedstock suitable for fast pyrolysis based on an existing fluidized bed reactor. Results indicate that control of feed particle size was very important to prevent problems of dust entrainment in the fluidizing gas as well as to prevent feeder hardware problems caused by large stones and aggregates. After physical separation and size reduction, nearly 70 wt.% of the trommel fines was obtained within the size range suitable for energy recovery using an existing fast pyrolysis system. This pyrolyzable fraction has similar thermochemical properties and could account for about 83% of the energy content of the 'as received' trommel fines sample. Thus indicating that suitably prepared trommel fines samples can be used for energy recovery, with more than 50% reduction in mass and volume of the original waste. Consequently, this can lead to more than 90% reduction in the present costs of disposal of trommel fines in landfills. In addition, the recovered plastics and textile materials could be used as refuse derived fuel.

*KEYWORDS: Trommel fines, biogenic municipal waste, physical pretreatment, fluidized bed reactor*

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## 1. INTRODUCTION

Trommel screens are commonly used in municipal solid waste (MSW) treatment plants. They can be used for both raw MSW and the air-classified light fractions (ACLF) of wastes to separate solid materials into different sizes (Glaub, Jones and Savage, 1982; Kim, Matsuto and Tanaka, 2003; Zhang and Banks, 2013). In the case of raw MSW, mechanical sorting and removal of glass, stones and aggregates are first carried out, then the waste is shredded and delivered for size classification on trommel screens. Fine materials, including soil, grit, and much of the biodegradable waste, fall through the screen as "unders", while plastic films and large paper products are retained on the screen as "overs" and may be recycled or marketed as refuse derived fuel (RDF) for energy recovery (Fitzgerald, 2013; Pitchell, 2014). For ACLF, which usually contains plastic film, paper and fine materials such as soil and grit, trommel screens are used to remove the fine fractions of ACLF in order to improve its recyclability or enhance its calorific value for use as RDF (Glaub, Jones and Savage, 1982; Kim, Matsuto and Tanaka, 2003; Zhang and Banks, 2013). Whether applied to raw MSW or ACLF, trommel screens often produce a by-product of mixed compositions, called trommel fines from the mechanical recycling of MSW. A schematic for MSW processing to obtain RDF which generates trommel fines is shown in Figure 1.

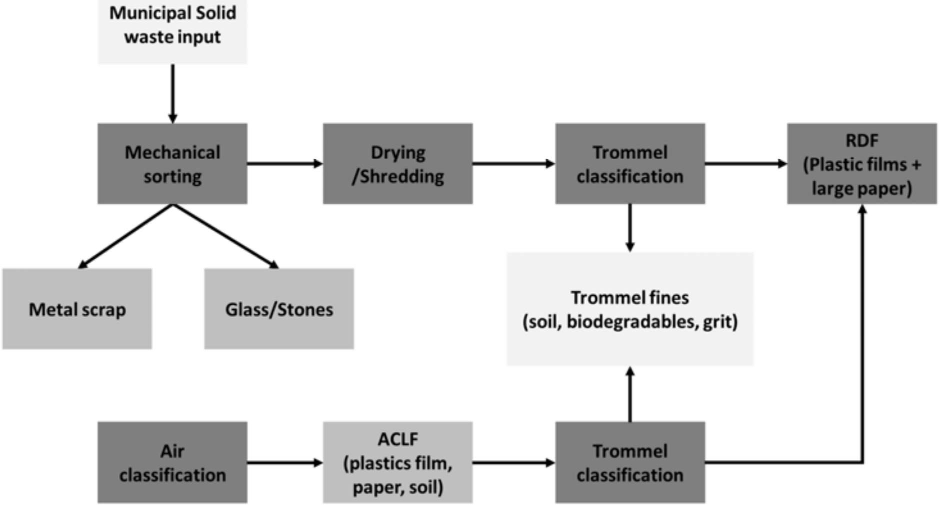

Figure 1. Mechanical recycling of MSW [Fitzgerald, 2013; Pitchell, 2014]

In general, trommel fines are made up of various materials that are less than 70 mm in size and contain both organic and inorganic components (Fitzgerald, 2013; Pitchell, 2014). The compositions of trommel fines thus depend on the initial type and composition of MSW, the severity of mechanical processing of the MSW and the design of the trommel screens. In general, the organic components of trommel fines include fibre, plastics, wood, food waste and textiles, with high calorific values and therefore can be used as an energy resource. The inorganic content of trommel fines includes inert materials such as stones, aggregates, glass and soil.

Trommel fines are now included in the UK's Landfill Tax (Qualifying Fines) Order 2015, and this requires landfill operators to conduct loss of ignition (LOI) tests to determine the correct tax liability for trommel fines; £2.65 per tonne dry basis for 'less polluting' waste with <10% LOI, or £86.10 per tonne, (the current higher rate) for waste exceeding 10% LOI. For most operators this means landfill tax for this type of waste will increase**.** For example, an operator producing 40 tonnes per day of trommel fines (dry basis) could see their landfill tax bill increase from about £40,000 to over £1,000,000 per year if it contains more than 10% LOI material (HMRC, 2014; Watts, 2016). Therefore the handling and disposal of trommel fines is now a major problem for the waste management industry, which requires further research. Some proposed methods include further separation and classification of components of trommel fines, for example, to recover smaller fractions of plastics and paper for RDF. This may be an expensive option and the physical separation of inorganics and organics on the basis of size and mass may no longer be feasible at smaller (< 2 mm) scales. Since the the volatile matter content of trommel fines is one of the main concerns for their disposal via landfill (HMRC, 2014; Watts, 2016), technologies are required to make the composition of trommel fines suitable for processing for operators and regulators.

Energy from Waste (EfW) technologies may therefore be a viable option for the handling of trommel fines as they can deliver significant benefits in terms of renewable energy recovery and reducing trommel fines to inert materials, which can be landfilled or used in the construction industry. In addition, EfW recovery processes can prevent some of the negative impacts of greenhouse gas emissions and land use issues that are associated with waste landfills. The energy generated from EfW processes can reduce the dependence on fossil fuel for power generation and contribute towards meeting UK renewable energy targets (Hackett et al., 2014). The term 'Energy from Waste' covers a range of processes, both thermochemical and biological, which recover value from waste in the form of energy. Thermochemical processes are usually faster and more robust than biological processes for mixed waste streams. For example, thermochemical processing can handle both biodegradable and non-biodegradable waste, whereas biological processing can only handle readily biodegradable waste (McKendary, 2002).

Some thermochemical processes extract the energy directly as heat (incineration) whereas others convert waste into different types of fuel for later use (pyrolysis and gasification). Fast pyrolysis offers an effective and sustainable technology to enable conversion of difficult-to-process solid wastes such as trommel fines due to their heterogenous composition thereby diverting such wastes from landfill. Among the different pyrolysis reactors, fluidized bed reactors can be operated to handle the fast pyrolysis of waste streams with high inorganic contents due to their reliability and ease to operate. Also they are quite simple to scale up from lab to commercial plant scale. However, the characteristics of the inert materials, particularly the particle size, brittleness and hardnesss, need to be considered in order to minimize the adverse effects on the pyrolysis process and products. Fine dust particles of less than 50 μm may be transported as dust out of the reactor by the fluidizing media and contaminate the pyrolysis products and potentially cause system blockage. In addition, the presence of stones, aggregates and glass can result in significant mechanical hardware problems, such as abrasive wear and tear of reactor interiors as well as blocking of moving parts.

During fluidised bed fast pyrolysis, more than 90% of the heat requirement for a feedstock particle is achieved via conduction through contact with the fluidized bed materials, (Bridgwater et. al 1999). Common bed materials include silica sand, which provides a constant temperature distribution within the reactor due to its very efficient heat transferability resulting from its high solid density. A fluidized bed reactor achieves the high heating rates at low residence times for complete thermal degradation by using small feedstock particle sizes (Bilbao et. al., 1994). Feedstocks used in a bubbling fluidised bed (BFB) fast pyrolysis reactor must be prepared to certain specifications. In most pilot and lab scale units, the particle size of feedstock must be between 0.25 - 2.00 mm for effective heat transfer and have been dried to below 10% moisture content (Bridgwater et al., 2000; Chen et. al., 2014). In addition, ash content of feedstock must be minimized as deposition and addition of ash to the bed material will lead to problems in fluidization as well as in heat transfer. However, high ash samples may be used in a fluidized bed reactor with adequate design consideraions. The pretreatment of solid waste is also important for reducing formations and emissions of trace levels of toxic organic pollutants, such as dioxins and dioxin-like compounds during pyrolysis process (Guorui et al., 2016; Rong et al., 2016; Yuyang et al., 2017).

This study describes a series of procedures for the pretreatment, characterization and preparation of a sample of biogenic-rich trommel fines for fast pyrolysis in a 300 g $h^{-1}$ BFB reactor. It also investigates the influence of particle size differentiation on sample characterization and thermal degradation properties. Detailed characterization in terms of calorific value and ash contents as well as particle size differentiation of the inert materials are needed to design a suitable fast pyrolysis process for this type of waste with highly variable carbonaceous composition and high contents of ash and inerts.

## 2. MATERIAL AND METHODS

### 2.1 Trommel fines feedstock

The sample used in this study was supplied by a UK commercial waste management company – Biffa Ltd from Leicester. The sample supplied was household waste after mechanical removal of the majority of the metals, glass, and plastics material, etc. Then the material was shredded to small particles and processed through a 10 mm rotary drum trommel screen to reduce the inhomogeneity of the sample. On the basis of size range, this feedstock has been classified as trommel fines (Fitzgerald, 2013; Pitchell, 2014).

### 2.2 Feedstock preparation

The feedstock was prepared based on the feeding requirement of a 300 g $h^{-1}$ bubbling fluidised bed fast pyrolysis reactor located at European Bioenergy Research Institute (EBRI), Aston University, UK. The reactor consisted of a twin metering screw and a fast screw feeder and usually requires feed particle size range of between 0.25 – 2 mm, with an operating temperature range of 400 – 550°C. The schematic of the BFB reactor is presented in Figure 2, which shows the main process units. To ensure that the trommel fines sample met the paricle size requiremnts of the fluidzied bed reactor, the schematic flow diagram in Figure 3 was designed to prepare the sample for fast pyrolsysis.

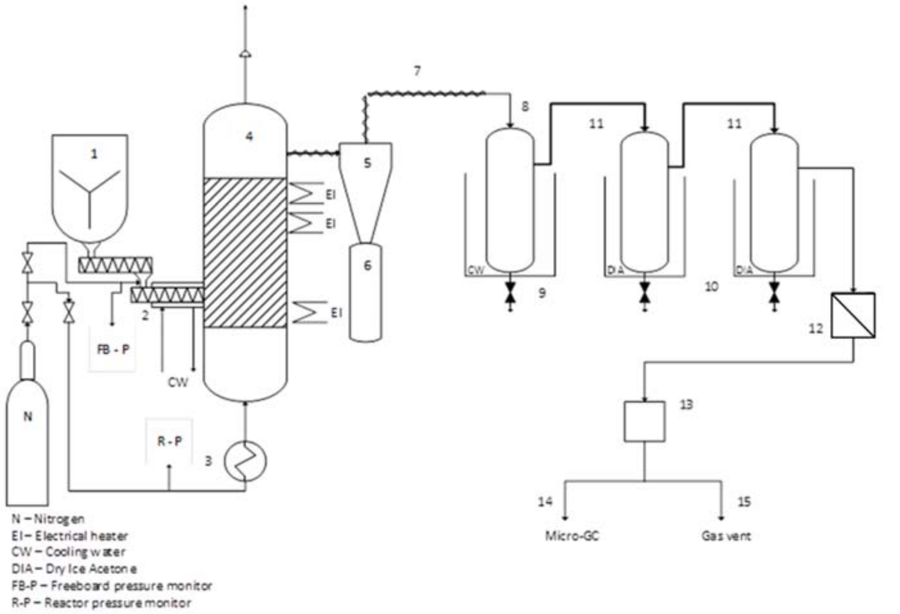

Figure 2. 300g/h bubbling fluidised bed fast pyrolysis rig set-up.

1 - feed hopper with twin screw feeder, 2 – fast screw, 3 – nitrogen preheater, 4 – fluidised bed reactor, 5 – cyclone, 6 – charpot, 7 – metal transition pipe, 8 – glass transition pipe, 9 – water cooled condenser, 10 – dry ice acetone condenser, 11 – ruber tansition pipe, 12 – cotton wool filter, 13 – gas meter, 14 – micro-gc, 15 – gas vent

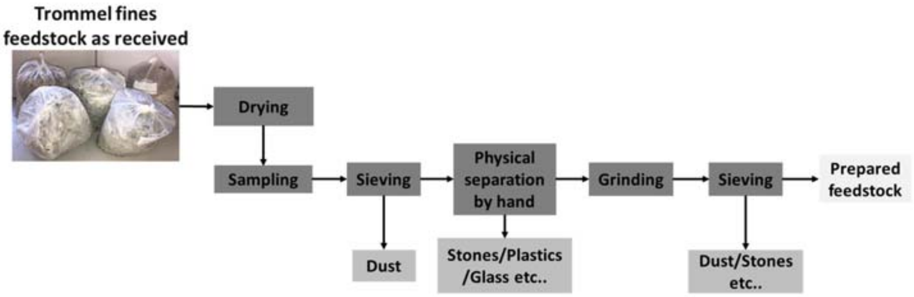

Figure 3. Block flow diagram for trommel fines feedstock preparation

### 2.2.1. Sampling

The coning and quartering method (Gerlach et al., 2002) was used to obtain a 3 kg representatative batch of the raw trommel fines sample and all the analyses were based on this sample batch.The method. which is used for sampling large quantities of material, consists of pouring the dried trommel fines into a conical heap upon a solid surface and dividing the heap by a cross. The two opposite corners are taken as the sample and the other two set aside.

### 2.2.2. Sieve analysis

Prior to sieving, the feedstock was dried in the oven at 60°C for 24 h. The sieve analysis was carried out according to ASTM D 422 standards using a set of sieves of different aperture sizes (> 3.5 mm) and Powermatic Sieve Shaker in order to separate the desired particle size (0.25 – 2mm) for pyrolysis experiments (ASTM, 2007°).

### 2.2.3 Grinding

The dried feedstock was ground with a Retsch Ltd., Germany, Heavy-Duty Cutting Mill, Type SM2000 with interchangeable screens of varying sizes (1-10 mm). The choice of screen was based on the feeding requirement of the fast pyrolysis reactor which are limited to <2 mm to prevent blockages and feeding problems during fast pyrolysis experiments and to bring the feedstock particles to the optimum pyrolysis temperature and minimize exposure to lower temperatures which favour the formation of char (Bridgwater, 2012).

### 2.2.4 Physical separation

Preliminary grinding test of the feedstock proved a challenge as the inorganics, textiles and plastics caused a blockage in the grinding mill (Supplementary Information SI1). To aid the grinding, process a physical separation step was added to the feestock preparation steps, which involved the manual removal of visible glass, stones, metal and plastics from the feedstock fraction with size range > 2 mm (Supplementary Information SI2). This step did not remove the entire inorganics and plastics present, but was found to be beneficial for the grinding process. Although this step can be achieved for a laboratory scale process, a more suitable method such as mechanical sorting would be needed for an industrial scale process in order to recover smaller fractions of plastics (< 10mm) for RDF and to reduce the abrasive wear and tear of reactor interiors as well as blocking of moving parts with respect to the twin and fast screw feeder of the fast pyrolysis system. For example, a water floatation process has been trialled, which led to the settling of heavy fractions (stones, sand and aggregates), with the suspension of finer relevant fractions. Details and results of this trial will be published later.

## 2.3 Physico-chemical analysis of trommel fines and fractions

The as recieved trommel fines samples and the different size range fractions from the sample preparation procedures were analysed to determine their thermochemical properties. Due to the heterogenous nature of the sample, the coning and quartering method (Gerlach et al., 2002) was used to obtain 100 g batch samples from the feedstock particle size fractions of <0.25 mm, 0.25 – 2 mm, 2 – 3.5 mm and 3.5 mm above after grinding and sieving to minimize deviations. Five replicate analyses were also carried out to account for sample varaiation, for which standard deviations were derived.

### 2.3.1. Proximate analysis

The proximate analysis of samples involved the determination of the moisture, ash, volatile matter and fixed carbon contents.

The moisture contents were determined according to ASTM E1756-01 principles on a dry basis (ASTM, 2007b). The percentage weight loss on a dry weight basis of a pre-weighed sample heated at 105°C to constant weight was recorded. Using the cone and quatering method, five aluminium boats with 4 – 5 g of the trommel fines sample were placed in an oven at 105°C for 6 h. The samples were then cooled in desiccators and re-weighed. The process was repeated hourly for each sample until constant weight was achieved.

The ash contents were determined according to the ASTM E1755-01 method (ASTM, 2007c). Five crucibles and lids were put in a Carbolite AAF1100 furnace and heated to 900°C for 3 h; crucibles were then removed from the furnace and cooled in a desiccator. The crucible weights were recorded and then approximately 4 - 5 g of dried feedstock was weighed into each crucible. The crucibles and samples with their lids placed at an angle were placed in a furnace and heated to 250°C at 10°C min$^{-1}$ and held for 30 min, then increased to 575°C for 5 h. After 5 h, the crucibles were removed and cooled in a desiccator for one hour. Each crucible was weighed to the nearest 0.1 g. Crucibles were replaced in a furnace and heated at 575°C for 1 h periods untill the crucible weigh was constant to within 0.3 g. The ash content was then obtained by dividing the weight of the samples by the pre-drying weight and expressed as a percentage of the original weight. The average of five samples was taken to further reduce the deviation.

Volatile matter was obtained on a moisture free basis. Volatile matter is the weight loss resulting from heating the sample under controlled conditions. The volatile content of the sample is taken as the weight loss at 950°C (ASTM D3175-89) for 7 min (ASTM, 1997). Five crucible weights were recorded and then approximately 4 to 5 g of dried feedstock was weighed into each crucible. The crucibles and samples with their lids fully sealed were placed in a Carbolite AAF1100 furnace and heated to 950°C and held for 7 min. Upon completion the oven was turned off the crucibles were removed and cooled in a desiccator. Each crucible was weighed, and the average of five samples was taken to further reduce the deviation.The fixed carbon value was obtained by difference.

### 2.3.2. Ultimate analysis

A Carlo-Erba 1108 elemental analyser was used to determine the elemental composition of a sample in terms of carbon, hydrogen and nitrogen. Other elements sometimes included in the analysis include, sulphur and oxygen; oxygen is often determined by percentage difference (Aiken, DeCarlo and Jimenez, 2007). Using the cone and quartering method, five different 5 g samples were dried in the oven at 60°C for 24 h prior to anlaysis and were ground using a coffee grinder. The cone and quartering method was used again to obtain about 1 g from each of the grounded samples for analysis. The results are reported on a dry basis to avoid reporting moisture as additional hydrogen and oxygen (Stahl et al., 2004).

### 2.3.3. Calorimetry

The bomb calorimeter experiment is the standard method (ASTM D2015) used to determine the higher heating value for a sample (ASTM, 2000). Results obtained from the bomb calorimeter experiment indicate the samples higher heating value (HHV). Using the cone and quartering method five different 5 g samples were dried in the oven at 60°C for 24 h prior to anlaysis. The cone and quatering method was used again to obtain approximately 1 g each from the 5 five different samples, which was burnt completely in an excess oxygen environment in a steel vessel, which is called a bomb using a Parr 6100 calorimeter. The reaction takes place at constant volume.

In addition, a mathematical equation (Eq. 1) correlated from the proximate analysis of different biomass from the literature (Parikh, Channiwala and Gosal, 2004) was used to calculate the heating value on a dry basis. The calculated and experimental results would be displayed for comparaions;

$$HHV_{(dry)} = 0.3536\ FC + 0.1559\ VM - 0.0078\ A \qquad \text{(Eq. 1)}$$

Where FC is fixed carbon, VM is volatile matter, and A is ash content.

#### 2.3.4. Thermogravimetric analysis (TGA)

To study pyrolysis under dynamic heating for the trommel fines feedstock, a PerkinElmer Pyris 1 thermogravimetric analyser was used. A pyrolysis heating rate of 10ºC min$^{-1}$ was used and heating from ambient temperature to 550°C in nitrogen flow of 30 ml min$^{-1}$. Using the cone and quartering method, five different 5 g samples were dried in the oven at 60°C for 24 h prior to anlaysis and were ground using a coffee grinder. The cone and quartering method was used again to obtain about 2 -3 mg from each of the five different grounded samples which was placed on a ceramic crucible on the analyser tray. The sample crucible was placed in a sensitive thermo-balance.The sample was subjected to heat from an external furnace to pre-set temperatures and heating rate. The weight loss as a result of thermal degradation was measured and recorded on the program software. All pyrolysis TGA experiments were conducted in an inert atmosphere of nitrogen. Each analysis was repeated 5 times.

### 2.4. Cold feeding trial for fast pyrolysis

After the sample preparation steps decribed above, the size fraction for fast pyrolysis was cold-fed into an existing blubbling fluidized bed reactor to monitor particle behaviour prior to actual pyrolysis tests. The feeders attached to the fluidised bed reactor consist of an air tight hopper with nitrogen purge with a Ktron KT-20 gravimetric speed regulated twin metering screws attached to a high speed feed screw, which is water cooled at the feed point to minimise pre-pyrolysis (see Figure 2). The feedstock feed rate can be adjusted using the computing system on the Ktron KT-20 gravimetric feeding system to adjust the speed of the feeding twin screw in to the fast screw; the set feed rate is then displayed on the system's LED screen.

## 3. RESULTS AND DISCUSSION

### 3.1 Particle size distribution in the trommel fines sample

Figure 4 shows the average particle size distribution by weight percent for five replicate 0.5 kg samples of the dried trommel fines feedstock before any sample preparation (grinding and separation). The results shows that only about 17.6 wt. % of the feedstock was initially within the size range (0.25 – 2 mm) that could be used for fast pyrolysis with an existing BFB. The 17.6 wt% comprised of fractions with particle sizes of 1 - 2 mm range accounting for an average of 11.5 wt% and 0.25 - 1 mm size range, which accounted for 6.13 wt% of the total weight of the trommel fines sample, respectively. Visual observation (Supplementary Information SI3) showed that these two size ranges were similarly made up of few tiny pieces of plastics and glasses, with the bulk of the fraction consisting of wood, paper/cardboard, textile material and sand; therefore could be suitable for energy recovery by fast pyrolysis.

A small fraction, accounting for 2.8 wt% was obtained with <0.25 mm particle size range and classified as dust, while 79.5 wt. % needed to undergo further processing. On average, the fraction with particle sizes >3.5 mm accounted for 68.2 wt% of the trommel fines. This size range comprised of mostly paper pellets, plastics, glass, stones, bones, miscellaneous wood, textile and metals. In addition, the fractions with particle sizes >2mm would require size reduction to enable feeding into the pyrolysis equipment. However, the presence of inert materials such as stones and glass would cause mechanical problems for the pyrolysis system.

Taken together, the two fractions with particle sizes >2 mm were combined and processed as follows; after physically removing the visible stones, glasses and plastics by hand, the remainder was ground and sieved to achieve a fraction with particle size range suitable for the fast pyrolysis equipment. For a large batch of waste the size range classification can be achieved using an industrial sieve but further research is required for appropriate method to remove the inorganics in a large batch of waste.

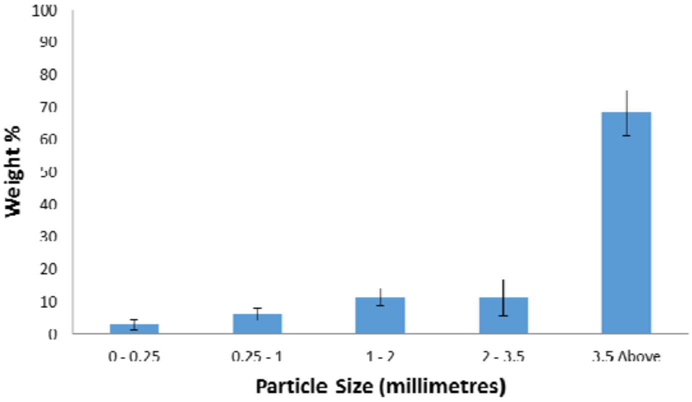

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Figure 4. Average particle size distribution of dried trommel fines sample before preparation (5 replicates)

### 3.2 Characterization of trommel fines in relation to particle size distribution

Table 1 shows the results of the proximate analysis of the trommel fines feedstock in different size ranges on a dry basis. The data in the table also reports the calculated HHV as well as the average of those obtained using a bomb calorimeter.

The proximate analysis data are relevant in determining the suitable quantity and thus the feeding rate for fast pyrolysis processing, which depends on the proportion of volatile matter in the feedstock and the rate of its thermal degradation. Also, the analysis offers a preview on the mass balance of the system.

The moisture content of the feedstock prior to processing was found to be 46.0 ± 3.23 wt.% on a dry basis, therefore requiring drying before processing to aid the grinding and sieving process. After oven drying at 60 °C the moisture content decreased to less than 13.5 wt.% for all fractions. However, the 2 – 3.5 mm fraction was found to retain the most moisture, possibly due to its high organic content, which enhanced moisture retention. The moisture in the trommel fines feedstock will eventually end up in the pyrolysis products, mainly in the liquid product. This is because the moisture in the feed must be evaporated before the thermal degradation of the particle will begin. The presence of water has also been shown to cause secondary reactions in some cases (He et al., 2009; Westerhof et al., 2007; Maniatis 1988; Gray et al., 1985). As water is an unwanted compound in most bio-oil, due to its lowering effect on the heating values, a moderate amount of moisture is known to impact positively on the viscosity of the oil product. Bridgwater et al. (2000) recommends that the moisture content for biomass for fast pyrolysis processes be around 10 % and this would be applicable to a biogenic-rich waste feedstock. Therefore, further drying may be required before the prepared feedstock could be used; however, this can be achieved via combustion of dusty fraction and char in the solid residues.

There was a clear indication of variation of ash content between the size fractions as seen in Table 1. The ash content decreased with increasing size fraction. The ash content of all the samples were between 31 – 54 wt.% on a dry ash free basis and shows significant difference between the size ranges, in particular, the particle size range of (0.25 – 2 mm) deemed for fast pyrolysis has an ash content of 42.1 ± 3.41 wt.% which is slightly similar to the as recieved sample. The inverse pattern was observed with the volatile content and the volatile content increased with particle size. There was no apparent trend with the fixed carbon with respect to particle size. From these results there was an indication that different fractions of the trommel fines can have significant differences in chemical properties. The high ash content in the feed, especially in the size fraction of 0.25 – 2 mm for the fast pyrolysis process was obviously due to the presence of high amounts of fine inorganics as the ash content is known to be dependent on the inorganic components of the feedstock. The high inorganics in the feed could arise from a number of reasons, such as the source of the feedstock and the technique used to separate the waste streams.The high ash content will lead to an increase in volume and weight of bed material in a fluidized bed pyrolysis process. Research has shown that inorganic compounds present in a feedstock promote the formation of char and gas at the expense of pyrolysis liquid yield. An increase in char and gas yield at the expense of bio-oil due to the presence of ash during pyrolysis was observed in a number of studies (Hodgson et al., 2010; Teng et al., 1998; Varhegyi et al., 1989; Sekiguchi et al., 1984). The reduced volatiles may be due to the size reduction process; for instance, the size reduction process (Figure 6) might have aided the degradation of the feedstock as well as eliminating certain materials (rubber, textile, and plastics) that would have improved the volatile content of the feed. The reduced volatiles in this feedstock were an early indicator of low liquid and gas yields from fast pyrolysis.

The experimental heating values for all the samples were between 7.8 – 13.2 MJ kg$^{-1}$, on a dry basis with the heating value increasing with increasing size fraction. This was an indication that pyrolysis liquids and bio-fuels with moderately high-energy content may be obtained from this feedstock. The experimental results compared well with the theoretical heating values (Table 1) as they were observed to be similar and increasing with size fraction.

Table 1. Results of average proximate analyses and heating values of trommel fines in relation to size ranges. (5 replicates)

| **ANALYSIS** | **UNITS** | **As received** | **< 0.25 (mm) [a]** | **0.25 – 2 (mm)[a, b]** | **2 – 3.5 (mm) [a]** | **3.5 Above (mm) [a]** |
|---|---|---|---|---|---|---|
| Ash content[a] | wt.% | 43.3 ± 4.81 | 53.8 ± 6.20 | 42.1 ± 3.41 | 34.9 ± 3.56 | 31.5 ± 2.08 |
| Volatile Matter[a] | wt.% | 46.6 ± 3.53 | 40.0 ± 3.03 | 49.7 ± 6.50 | 56.7 ± 3.28 | 60.1 ± 4.65 |
| Fixed Carbon[c] | wt.% | 11.1 | 6.20 | 8.15 | 8.39 | 8.38 |
| Moisture content | wt.% | 46.0 ± 3.23 | 9.56 ± 1.01 | 12.5 ± 3.04 | 13.2 ± 0.75 | 12.5 ± 0.92 |
| Bomb Calorimeter[a] | MJ kg$^{-1}$ | 11.6 ± 2.59 | 7.78 ± 0.87 | 11.8 ± 0.27 | 13.2 ± 0.59 | 12.5 ± 0.41 |
| Calculated[a] | MJ kg$^{-1}$ | 10.7 | 8.01 | 10.3 | 11.5 | 12.1 |

[a] dry basis; [b] prepared size fraction for fast pyrolysis experiments, [c] calculated by difference

### 3.3. Physical preparation of trommel fines for fast pyrolysis

Due to the limitations of the feeding system (allows only particle sizes < 2 mm) of an existing fast pyrolysis reactor, it was decided to test-feed the reactor with the combined fractions with particle size ranges covering between 0.25 – 2 mm. This initial tests revealed serious problems of dust entrainment and deposition throughout the downstream parts of the pyrolysis system (condensers and filters), as shown in Figure 5. Apparently, the amount of dust (< 0.5 mm) produced during the feeding increased due to the vibration of the fast screw rotating at a pre-set rate of 100 rpm. This dust was easily transported through the rig via the nitrogen gas connected to the feeding system and the fluidizing nitrogen in the reactor. This could easily pose significant problems during the operation of the pyrolysis equipment. Firstly, the dust could settle along narrower pipes and cause blockage which would in turn lead to build up of pressure in the rig. Such pressure build-up could lead to explosion and loss of containment. Secondly the dust, which still contains combustible organic matter may be susceptible to dust explosion with serious consequences. Thirdly, the dust would contaminate the consensable pyrolysis products downstream, cause blockage to the fast screw when feeding and affect the safe operation of the rig. The solution to this challenge was to reduce the content of the fine dust particles by physical separation via sieving. Hence, when the feed particle size was adjusted to 0.5 – 2 mm, the dust deposition and transportation through the rig stopped. Although, this would decrease the fraction obtained for energy recovery via fas pyrolysis, the safety of operation was deemed of much higher importance than a few losses.

Hence, this particle size range was considered for the fast pyrolysis of the trommel fines, following the sample preparation protocol depiected in Figure 6. As shown in Figure 6, a 3 kg batch of trommel fines was used directly for the sample preparation involving physical separation by hand, grinding and seiving. Table 2 shows the results of the preparation protocol. After feed preparation, 69.4 wt. % of the 3 kg trommel fines batch was obtained with a suitable particle size range for the fast pyrolysis process (0.5 – 2mm).

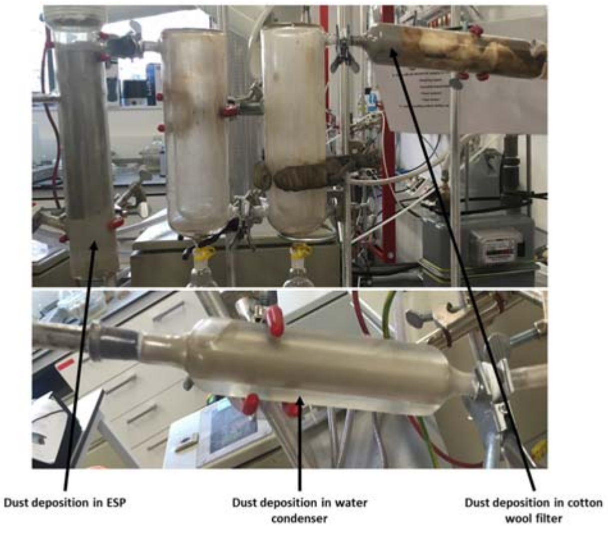

Figure 5. Accumulation of dust in downstream parts of a fast pyrolysis rig during feeding trial

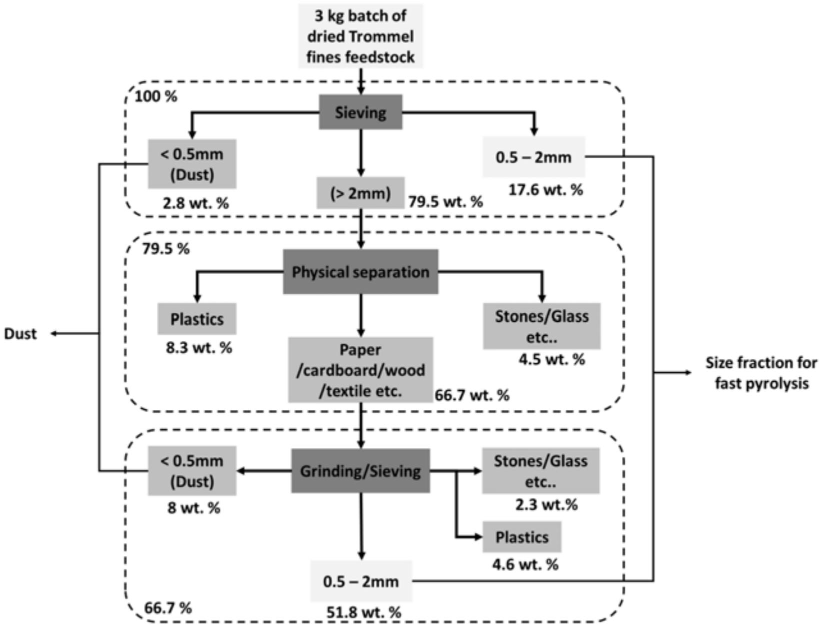

Figure 6. Detailed scheme for trommel fines feedstock preparation

Table 2. Updated summary of trommel fines main components from feedstock preparation

| Fractions | Weight % |
|---|---|
| < 0.5 mm | 10.8 |
| 0.5 - 2mm* | 69.4 |
| Stones/Glass etc. | 6.8 |
| Plastics | 12.9 |
| TOTAL | 99.9 |

*** Size fraction for fast pyrolysis**

An enlarged  photographs of the 'as-recieved' sample and the prepared sample fraction deemed suitable for fast pyrolysis is shown in Figure 7. The calorific value (HHV) of the fraction for pyrolysis was determined to be 13.8 ± 0.32 MJ kg$^{-1}$. This value is slightly higher to the value for the 0.25 – 2 mm fraction shown on Table 2, indicating that the removed dusty fraction composed of mostly inert materials. In total, the 0.5 – 2 mm fraction represented 82.6 % of the energy content of the original batch of trommel fines. Overall, some 10.8 wt. % (<0.5 mm) comprised of mainly dust (ash), which was eliminated. This fraction could be burnt in an industrial process to provide heat for the pyrolysis porcess as it had an appreciable heat content (7.8 MJ $kg^{-1}$). The physical separation by hand yielded 12.9 wt. % and 6.8 wt.% of plastics and inorganics (stones, bone, etc.) repectively. On an industrial scale, the plastics and textiles could be recycled for RDF and while the inorganics (glass and stones) can be used in construction.

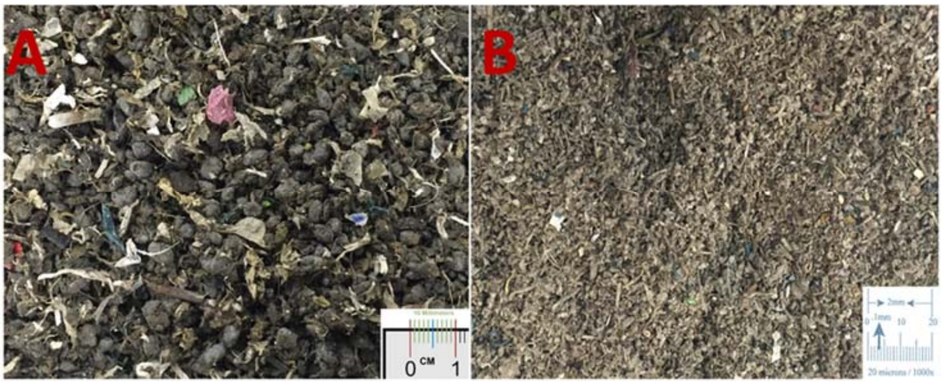

Figure 7: A. Trommel fines as received (<10 mm size range); B. Prepared trommel fines fraction (0.5 – 2 mm size range) for fast pyrolysis

The ultimate analysis, on dry, ash-free basis, of the prepared trommel fines feedstock (size range 0.5 - 2 mm in Table 3) shows elemental compositions similar to literature data for a refused derived fuel from municipal solid waste (MSW) as reported by other authors (Efika, Wu and Williams, 2012; Blanco et al., 2012; Materazzi et al., 2015). The prepared trommel fines feedstock has a lower carbon content of 34 wt. % when compared to literature data range of 43 - 62.1 wt. % for RDF. The oxygen contents of the feedstock also differ with this feedstock having lower oxygen content of 13.7 wt.% when compared to literature, which stands at between 26.52 and 37.9 wt.%. These differences could be attributed to the source and composition of the waste. One clear observation was that the feedstock has a significantly high nitrogen content of 4.79 wt. % when compared with other MSW literature data of 0.1 - 1.82 wt. % (Efika, Wu and Williams, 2012; Blanco et al., 2012; Materazzi et al., 2015). The nitrogen contents also serve as an indication of the possibility of NOx compounds forming during the oxidative thermochemical processing of the feedstock (Diebold, 2002). This is undesirable in terms of environmental considerations. The feedstock showed sulphur contents like those reported for MSW in literature (Materazzi et al., 2015).

Table 3: Ultimate analysis of trommel fines 0.5 - 2 mm size range (5 replicates)

| **Elements** | ***Wt.%** |
|---|---|
| Nitrogen | 2.75 ± 3.16 |
| Carbon | 33.71 ± 6.93 |
| Hydrogen | 4.62 ± 0.92 |
| Sulphur | 0.26 ± 0.20 |
| Oxygen | 17.06 ± 8.21 |

*remainder was classified as ash

Thermal degradation rate of solid fuels is very important in the design of a fluidized pyrolysis system. Fundamental to the degradation rate are the rates of bond breaking, formation and devolatilisation of small stable molecules. The TGA and DTG curves of the prepared trommel fines feedstock are shown in Figure 8. Three major weight loss steps are evident from the DTG curve. The initial weight loss step, which accounted for the removal of moisture from the feedstock, occurred between 40 and 106°C. The second weight loss step happened between 110 and 390 °C. The second step was the major pyrolysis process and the inflection point of this step was at 350 °C and that showed the temperature at which weight loss was at its maximum. This loss can be attributed to the degradation of components such as hemicellulose, cellulose and lignin of the sample. The third weight loss step occurs between 400 and 523°C. The small weight loss with a maximum degradation temperature of about 500°C may be attributed to the small amount of fine plastic particles remaining in the sample. The total weight loss as can be seen on the TGA curve of the trommel fines feedstock stands at about 54% between 40 ºC and 550ºC, which is similar to the upper limit sum of VM and moisture contents of the sample (53.7 wt%).

Clearly, Figure 8 confirms the high ash content of the prepared trommel fines sample but it also shows that the sample contains a significant proportion of volatile mater from which energy can be obtained via fast pyrolysis. Recovery of this energy will be important to meet landfill disposal requirements in terms of the loss on ignition (LOI) limits and for sustainable waste management. The results of the ash content analysis of the feedstock, suggest that about 50% of the feedstock can be used for energy recovery and diverted from landfill.  In addition, the seemingly inert ash product may be used in construction. This will reduce the amount of landfill tax an operator that produces 40 tonnes a day would pay from over £1,000,000 to less than £60,000. This estimate takes into consideration the reduction in mass and volume of waste due to energy recovery as well as the reduced tarriff applicable to the landfilling of ash-rich, low LOI-bearing solid residues.

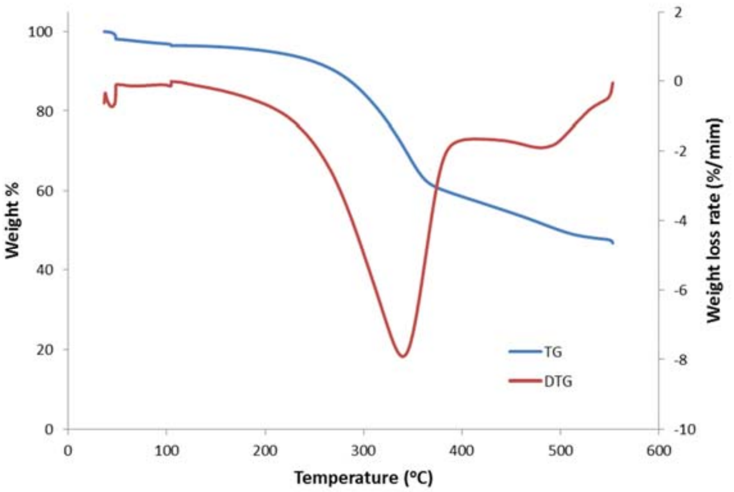

Figure 8. TG and DTG curves of trommel fines

## 4. CONCLUSIONS

A sample of trommel fines obtained from a UK Waste Mangement company showed a wide range of particle sizes and contained mixtures of different materials from plastics, paper and cardboard to stones and bricks. The increasingly tight regulations for disposal of trommel fines in landfills, especially in terms of LOI limits, have necessitated the need to investigate alternative processes for its management. Thermochemical process via fast pyrolysis looks like a plausible solution, however the physical characterstics of trommel fines would need to be adjusted to meet the requirements of fast pyrolysis. Initial results of proximate analyses showed that different size fractions of trommel fines have differences in properties. Ash, volatile content and heating values varied in relation to the range of particle sizes. However, the removal of glass, metals and inert materials such as stones etc., which do not contribute to the energy content of the waste, is highly recomended to reduce the volume of waste and minimize reactor damage which can be done via physical separation.

Although, manual separation appears plausible for a lab scale process, further research is required for inorganic removal pretreatment method appropriate for a large batch of waste. This is a topic for future work. In addition, dust formation is a potential hazard during the feeding for fast pyrolysis of trommel fines, but this can be minimized by using the appropriate particle size range after size reduction via screening, grinding and sieving. This preliminary work suggests that appropriate feedstock preparation is needed to make thermal recovery of energy possible from heterogeneous and complex waste materials such as trommel fines.

Energy recovery from trommel fines has a potential to reduce the cost of handling and disposal this heterogenous waste. Fast pyrolysis tests using the fulidized bed reactor will be carried out of the 0.5 – 2 mm fraction in future to investigate its suitability to handle this type of sample. In addition, the possibility of designing a reactor stuitable for the pyrolysis of trommel fines would be investigated.

## AKNOWLEDGEMENTS

The authors are grateful to the European Bioenergy Research Institute at Aston University for their continuous support.

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