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Research Paper

Benefits of dry comminution of biomass pellets in a knife mill

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ARTICLE INFO

Article history:
Received 19 February 2017
Received in revised form
21 May 2017
Accepted 30 May 2017

Keywords:
Biomass
Knife mill
Particle size
Particle shape
Pellet durability
Drying

The potential benefits of dry comminution in a knife mill for a diverse range of biomass pellets are explored. The impact of dry comminution on energy consumption, particle size and shape, is examined as well as the link between milling and mechanical durability. Biomass pellet comminution energy was significantly lower (19.3–32.5 kW h t^{-1} [fresh] and 17.8–23.2 kW h t^{-1} [dry]) than values reported in literature for non-densified biomass in similar knife mills. The impact of drying was found to vary by feedstock. Dry grinding reduced milling energy by 38% for mixed wood pellets, but only 2% for steam exploded pellets. Particle size and shape, particle distribution dispersion, and distribution shape parameters changes between fresh and dry milling were also material dependent. Von Rittinger analysis showed that to maximise mill throughput, pellets should be composed of particles which can pass through the screen and thus have a neutral size change. A strong correlation was found between pellet durability and energy consumption for fresh biomass pellets. Dry grinding has the potential to significantly reduce energy consumption without compromising the product particle size, as well as enhancing product quality and optimising biomass pellet comminution and combustion.

1. Introduction

Historically biomass comminution research has primarily focused on non-densified woody and herbaceous biomass using hammer, knife, or cutting mills (Adapa, Tabil, & Schoenau, 2011; Arias et al., 2008; Bitra, Womac, Chevanan, et al., 2009; Bitra, Womac, Yang, et al., 2009; Chevanan et al., 2010; Esteban & Carrasco, 2006; Ghorbani, Masoumi, & Hemmat, 2010; Gil & Arauzo, 2014; Gil, Arauzo, Teruel, & Bartolomé, 2012; Himmel et al., 1986; Laskowski & Lysiak, 1999; Liu, Wang, & Wolcott, 2016; Mani, Tabil, & Sokhansanj, 2004; Miao, Grift, Hansen, & Ting, 2011; Paulrud, Mattsson, & Nilsson, 2002; Phanphanich & Mani, 2011; Repellin, Govin, Rolland, & Guyonnet, 2010). Hammer mills are commonly used in bioenergy applications, and biomass is often densified to improve transportation, conveying, and comminution in power stations (Obernberger & Thek, 2010). Coal mills converted to comminute biomass often retain their drying section to dry comminute biomass (Livingston, 2012). Previous studies have looked into the impact of moisture on wood pellet

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http://dx.doi.org/10.1016/j.biosystemseng.2017.05.011

Nomenclature

AR	Particle Aspect Ratio (dimensionless)
C	Circularity of a particle (dimensionless)
C_c	Coefficient of curvature (dimensionless)
C_u	Uniformity coefficient (dimensionless)
d'	Rosin–Rammler characteristic particle size (μm)
d_{10}	Effective particle diameter (μm)
d_{80}	Particle size at 80th percentile of cumulative distribution (μm)
d_{gw}	Geometric mean diameter by mass (μm)
D_U	Mechanical Durability (%)
E_e	Total effective specific energy (kW h t^{-1})
E_{eva}	Evaporation energy (kJ)
GS_i	Inclusive graphic skewness (dimensionless)
HHV_d	Dry Higher Heating Value (J g^{-1})
hs	Distribution geometric standard deviation of high region (dimensionless)
K_g	Geometric kurtosis (dimensionless)
ls	Distribution geometric standard deviation of low region (dimensionless)
M	Moisture content (%)
MRS	Mass Relative Span (dimensionless)
n	Rosin–Rammler size distribution parameter (dimensionless)
$R(d)$	Rosin–Rammler cumulative percentage undersize mass (%)
$Symm$	Symmetry of a particle (dimensionless)
φ	Sphericity of a particle (dimensionless)

comminution (Temmerman, Jensen, & Hébert, 2013), but no studies have compared the dry comminution of woody, herbaceous, fruit, and thermally treated biomass pellets commonly used in pulverised fuel power stations has been detailed in literature, which this study aims to address.

Coal and biomass have different compositions and require different comminution processes for optimal particle size reduction (Blair, 2014). Coal is a brittle material which fragments easily under the application of compressive forces, while biomass is a soft material which is more readily processed by the application of shear forces. Biomass milling energy consumption is influenced by the material variables of moisture content, initial particle size, and composition (Carone, Pantaleo, & Pellerano, 2011; Gil, Arauzo, & Teruel, 2013; Kobayashi et al., 2007; Miao et al., 2011; Temmerman et al., 2013). In full scale coal mills, coal is dried during the milling process to remove moisture and increase brittleness (Scott, 1995). However dedicated biomass mills are generally hammer mills with no drying section. Biomass is dried prior to densification (Tabil, Kashaninejad, & Adapa, 2011) and coal mills converted to comminute biomass continue to use the in situ drying systems, but operate at lower temperatures (Livingston, 2012). Particle size and shape are crucial for optimal combustion (Mandø, Rosendahl, Yin, & Sørensen, 2010), but the influence of dry comminution on pellet particle shape is unknown.

Densified biomass comminution involves two stages fracture; the breaking down of the weak bonds holding the pellets together, and the size reduction of the pellet particles (Williams et al., 2016). Biomass densification aims to increase the bulk density of the biomass from 40 kg m^{-3} to 200–600 kg m^{-3} in order to reduce transportation costs (Gilbert, Ryu, Sharifi, & Swithenbank, 2009). International standards exist for biomass pellet dimensions, moisture content, and mechanical durability (The British Standards Institution, 2014a, 2014b). The mechanical durability of pellets is heavily influenced by material composition, pre-conditioning processes and densification equipment (Kaliyan & Vance Morey, 2009; Rabier et al., 2006). Additionally the densification process temperature, material moisture content and particle size influence the pellet durability (Carone et al., 2011; Fasina, 2008; Mani, Tabil, & Sokhansanj, 2006). Water plays a central role in the binding mechanisms in the pellets (Samuelsson, Thyrel, Sjöström, & Lestander, 2009), and moisture content attainment has been shown to significantly influences pellet bulk density, particle density and durability (Fasina, 2008; Guo, Tabil, Wang, & Wang, 2016; Theerarattananoon et al., 2011). Thermal treatments are also known to alter the strength of pellets (Shaw, Karunakaran, & Tabil, 2009).

Apart from the olive pellets, the energy consumption, particle size and shape data for the fresh samples was previously compared to the comminution of the same samples in several other mills (Williams et al., 2016). This study builds upon this previous research to provide a novel comparison of the results to the comminution of the samples in a dry state within a knife mill. It provides novel data and analysis on the relationship between mechanical durability and mill energy consumption, and how the Von Rittinger analysis can be used to assess the fracturing of pellets during comminution. Ultimately the study aims to assess what considerations which should be taken into account if biomass is dried during comminution in industrial power systems.

2. Materials & methods

2.1. *Materials & pre-milling characterisation*

Six diverse types of densified biomass and one powdered biomass material (olive cake) were tested in this study. Portuguese mixed wood pellets (mainly pine (*Pinus*) with eucalyptus (*Eucalyptus grandis*)), Russian sunflower husk (*helianthus annus* L.) pellets, and Spanish olive cake (*Olea europaea*; a residual waste mix from olive oil production) were provided by EDF Energy plc. South African eucalyptus (*Eucalyptus grandis*) pellets, olive pellets, miscanthus (*Miscanthus* × *giganteus*) pellets, and American steam exploded white wood chip pellets were provided by E.ON UK plc. The dry higher heating values (HHV_d) of the samples were found using an IKA C5000 Bomb Calorimeter (Staufen, Germany) in accordance with BS ISO 1928:2009 (The British Standards Institution, 2009b). Certified benzoic acid tablets were used as a standard, and the sample weight was calibrated to give the same temperature rise as the standard. Each sample was tested in triplicate.

The total moisture content (M) was calculated on a wet basis in accordance with BS EN 14774-1:2009 (The British

Standards Institution, 2009a). 300 g ± 1 g of each sample was dried in a Thermo Scientific Heraeus UT6 (Waltham, MA, USA) forced-air oven at 105 °C ± 2 °C for 24 h. After drying the weight of the sample was recorded and used to calculate the moisture content of the biomass, with each sample being tested in triplicate. The dried samples used in the milling tests were dried under the same conditions, and then placed in zip-lock sealed bags until use.

To analyse the moisture reabsorption of pellets in atmosphere, 100 g ± 1 g of each sample was dried according to BS EN 14774-1:2009 and then placed on a Ohaus Pioneer balance PA4102c (Nänikon, Switzerland) for 24 h. The weight was logged via a laptop using the Ohaus data acquisition software at 10 s intervals over a 24 h period in an air conditioned laboratory. The moisture reabsorbed is represented by the percentage increase in mass after 24 h. Temperature and humidity of the space during the reabsorption tests were measured in 5 min intervals using a Lascar Electronics UK EL-USB-1 USB temperature and humidity data logger (Salisbury, UK). The average room temperature was 19.3 °C ± 0.8 °C with an average humidity of 50.2% ± 4% for all tests. To analyse the moisture reabsorption of biomass in sealed storage, 100 g ± 1 g of each sample was dried to BS EN 14774-1:2009 and then stored in zip-locked bags and weighed. After 6 days the moisture increase was found by weighing the samples and zip-lock bags and noting the mass increase.

2.2. Pellet durability

Pellet durability is a measure of the resistance of densified fuels to shocks and/or abrasion as a consequence of handling and transportation processes (The British Standards Institution, 2015). Pellet durability of the biomass pellets was evaluated in accordance with BS EN ISO 17831-1. A test portion (m_E) of 500 g ± 0.1 g was placed in the tumbling box device, and then tumbled at 50 rpm ± 2 rpm for 500 rotations. The sample was then passed manually through a 3.15 mm diameter sieve suitable for manual screening in accordance with BS ISO 3310-2:2013 (The British Standards Institution, 2013). After sieving the sample remaining on the sieve was weighed (m_A). The test was performed in duplicate. The mechanical durability of pellets (D_U) was calculated as follows:

$$D_U = \frac{m_A}{m_E} \cdot 100 \tag{1}$$

2.3. Knife mill

The comminution trails were conducted in a Retsch SM300 knife mill (Hann, Germany). The knife mill is a continuous throughput mill, and classifies the sample via a fixed screen. The knife mill uses high shear forces to fracture and cut the material into smaller fragments through attrition. The mill has a 3 kW drive with an additional auxiliary flywheel mass, and a speed range of 700–3000 rpm. A 4 mm screen was used at a speed of 1500 rpm, and the sample was fed continuously via a Fritsch Laborette vibrating bed feeder (Idar-oberstein, Germany) at an average feed rate of 9 kg h^{-1}. A 400-ml of sample was used for each run, and all milling trials were repeated in triplicate. EDF Cottam coal fired power station uses 3.8 mm screens on a hammer mill for the comminution of various biomass pellets, and thus a 4-mm screen size was selected to match this comminution screen size.

The first stage of the experiment was to conduct milling on all the selected samples in their "as received" or fresh state (Williams et al., 2016). The second stage repeated the experiment for dried samples. The samples were dried as described in Section 2.1, and then stored in zip-locked bags and used within 7 d of drying. All tests were repeated in triplicate. Energy consumption was recorded using an Elcomponent SPCPro energy meter and data logger (Bishop's Stortford, UK). Power data was processed using the Elcomponent Powerpack Pro software. The total specific energy (E_s) was calculated by integrating the power–time curve obtained from the data logger and then dividing by the material mass to give the total energy consumed during the milling process (Gravelsins & Trass, 2013). The total specific effective energy (E_e) was obtained by subtracting the specific idle energy from total specific energy for the run as measured by the energy logger (Bitra, Womac, Chevanan, et al., 2009; Himmel et al., 1986; Miao et al., 2011):

$$E_e = \int_0^t \frac{P dt}{m} - \int_0^t \frac{P_i dt}{m} \tag{2}$$

where P is the instantaneous power consumption (kW), P_i is the average idle power consumption (kW), t is time (hour), and m is mass (tonne). Von Rittinger's theory of comminution (von Rittinger, 1867) was used to compare the relationship between specific effective energy consumption and particle size reduction of the knife mill and is defined as:

$$E_e = K\left(\frac{1}{d_2} - \frac{1}{d_1}\right) \tag{3}$$

where K is the material characteristic constant, d_1 is the 80th feed passing size (μm), and d_2 is the 80th product passing size (μm). The evaporation energy, E_{eva}, was calculated using the latent heat of evaporation (2257 kJ kg^{-1}), the moisture content (M) of the material (Section 2.1), and the original mass of the material (m):

$$E_{eva} = 2257 \cdot M \cdot m \tag{4}$$

2.4. Particle size distribution by sieving and characterisation

Particle size distributions (PSD) were determined by sieving the milled product in accordance with BS EN 15149-2:2010 (The British Standards Institution, 2010). The samples were sieved into 16 size fractions; 4750, 3350, 2360, 1700, 1180, 1000, 850, 600, 425, 300, 212, 150, 75, 53, 45, 38 μm sieves. Sieving was conducted on a Retsch AS200 control vibratory sieve shaker (Hann, Germany). Each sieving stage was conducted for 15 min at 3 mm amplitude. The PSD of the biomass pellet particles prior to densification (denoted as pre-densified PSD) were obtained in accordance with BS EN 16126:2012 (The British Standards Institution, 2012). The PSD was fitted to the Rosin–Rammler distribution equation, which was originally developed to describe the distribution of coal fines from coal mills (Rosin & Rammler, 1933), and has been shown to have a good fit for

biomass comminution in hammer mills (Bitra, Womac, Chevanan, et al., 2009; Ghorbani et al., 2010; Gil et al., 2012):

$$R(d) = 100\left(1 - e^{-\left(d/d'\right)^{n}}\right) \quad (5)$$

where R is cumulative percentage undersize mass (%), d is particle diameter (μm), d' is the characteristic particle size (μm), defined as the size at which 63.2% ($1 - 1/e = 0.632$) of the particles (by weight) are smaller, and n is the Rosin–Rammler size distribution parameter (dimensionless). The Rosin–Rammler parameters were found using the Matlab® GUI Tool developed by Brezáni and Zelenak (2010).

The PSD profiles were characterised through 13 different parameters relating to particle size, dispersion, and distribution shape. The size parameters were characterised by the effective particle size (d_{10}), the 80th percentile particle size (d_{80}), and geometric mean diameter by mass, d_{gw}, which was calculated according to ANSI/ASAE S319.4 (ANSI/ASAE, 2008). The dispersion parameters were represented by the distribution geometric standard deviation of high region ($hs = d_{84}/d_{50}$), the distribution geometric standard deviation of low region ($ls = d_{50}/d_{16}$), and the mass relative span ($MRS = (d_{90} - d_{10})/d_{50}$). The uniformity coefficient ($C_u = d_{60}/d_{10}$) and coefficient of curvature ($C_c = (d_{30})^2/(d_{60} - d_{10})$) are used to give a quantitative means for describing the shape of the grading curve, and have been used to describe the dispersion of biomass PSD (Bitra, Womac, Yang, et al., 2009; Budhu, 2011; Gil & Arauzo, 2014). The distribution shape parameters were represented by skewness and kurtosis. The inclusive graphic skewness (GS_i) measures the asymmetry of a distribution and was calculated according to the formula denoted by Folk (Folk, 1974). The geometric kurtosis (K_g) measures the peakedness or flatness of the distribution, relative to the log-normal (Bitra, Womac, Yang, et al., 2009), and was calculated as per the formula denoted by Folk (1974).

2.5. Particle shape distributions and characterisation

A Retsch Camsizer® P4 particle analyser (Hann, Germany) was used to characterise the shape characteristics of the samples through 3D digital image analysis. The sample was split using a riffle box prior to measurement, resulting in a sample size of approximately 2 million to 5 million particles, depending on the fineness of the sample. Each sample was tested in triplicate. The results of the particle shape characteristics are based on the shortest chord diameter (d_{c_min}) (Retsch Gmbh, 2009), and can be considered as equivalent to the particle size achieved from sieving. The aspect ratio (AR) is the ratio of d_{c_min} to the maximum Feret diameter (d_{Fe_max}), which is the longest distance between two parallel tangents of the particle at any arbitrary angle (Retsch Gmbh, 2009). The measured sphericity is the operational sphericity (φ) as defined by Krumbein and Sloss (1963):

$$\varphi = \frac{d}{a} \quad (6)$$

where a is the diameter of a circumscribed sphere around a particle, and d is the diameter of a sphere of the same volume as the particle, with 1 being a perfect sphere. Circularity (C) is the ratio of the area equivalent diameter of the particle and the perimeter equivalent diameter of the particle. Circularity measures how closely a particle resembles a circle, considering the smoothness of the perimeter. Circularity is a measure of the particle roundness (Wadell, 1934), with an ideal circle having a value of 1 (Retsch Gmbh, 2009). The level of symmetry in the particles of a given size class is given by:

$$Symm = \frac{1}{2}\left(1 + min\left(\frac{r_1}{r_2}\right)\right) \quad (7)$$

where r_1 and r_2 are distances from the centre of area to the borders in the measuring direction. For asymmetric particles *Symm* is <1. If the centre of area is outside the particle i.e. $r_1/r_2 < 0$, then *Symm* <0.5.

3. Results and discussion

3.1. Moisture content

The starting point of this study was to ascertain the moisture content of the fresh pellets and their hygroscopic properties after drying. Table 1 details the pellet moisture contents, moisture reabsorption of dried pellets after 24 h, and moisture reabsorption of dried pellets stored in zip-lock bags for 6 days. Olive cake had the highest moisture content (17.9%), and steam exploded pellets (7.2%) and miscanthus pellets (7.6%) the lowest. All other samples had moisture contents between 9.4% and 11.8%. Pellets which were stored in zip-lock bags exhibited minimal uptake of moisture over 6 days

Table 1 – Moisture content and moisture reabsorption for exposed and zip-lock bag stored biomass. The average room temperature was 19.3 °C ± 0.8 °C with an average humidity of 50.2% ± 4% for the moisture reabsorption tests. Data are the mean of 3 repetitions.

Sample	Moisture content, M (%)	Increase in moisture content of dried samples after 24 h (%)	Increase in moisture content of dried samples after for 6 d of sealed storage (%)
Eucalyptus pellets	10.5	4.6	0.17
Miscanthus pellets	7.6	4.5	0.16
Mixed wood pellets	9.4	4.3	0.24
Olive cake	17.9	2.1	0.27
Olive pellets	11.2	1.3	0.29
Sunflower pellets	11.8	4.1	0.14
Steam exploded pellets	7.2	2.0	0.23

(0.14–0.29%). Thus as the dry comminution trials used ziplock stored dried pellets and used within 7 d of drying, the samples were taken as dry at the point of use.

All pellets reabsorbed moisture after drying. Olive pellets exhibited the lowest moisture uptake after 24 h (1.3%), and eucalyptus pellets the highest (4.6%). However, the moisture reabsorption does appear to be biomass group dependent. All the woody (mixed wood and eucalyptus) and herbaceous (sunflower and miscanthus) pellets exhibited similar levels of moisture reabsorption (4.1–4.6%). Steam exploded pellets, olive cake, and olive pellets only reabsorbed half as much moisture as the woody and herbaceous pellets (1.3–2.1%). Interestingly, the olive pellets did not disintegrate in the pellet disintegration test. This indicates that the olive pellets are hydrophobic. Wet torrefaction is also known to enhance the hydrophobic nature of biomass (Acharjee, Coronella, & Vasquez, 2011). Therefore, olive materials and steam exploded pellets uptake less moisture than woody and herbaceous pellets after drying.

3.2. *Energy consumption*

Figure 1 reports the fresh and dry specific effective energy (E_e) for the comminuted biomasses, which represents the energy solely required for comminution. In accordance with previous studies for non-densified biomass (Gil & Arauzo, 2014; Gil et al., 2012, 2013; Himmel et al., 1986; Liu et al., 2016; Miao et al., 2011) and for woody pellets (Temmerman et al., 2013), dried samples exhibited lower specific energy consumption than fresh samples. However, the influence of drying on energy consumption was found to vary by feedstock. The E_e range for fresh samples was between 19.3 kW h t^{-1} for fresh sunflower pellets and 32.5 kW h t^{-1} for fresh mixed wood pellets. In contrast, the E_e range for the dried pellets was much closer; 17.8 kW h t^{-1} for dried sunflower pellets and 23.2 kW h t^{-1} for dried olive pellets. Thus dry comminution results in more congruent milling energies across different biomass types.

Moisture content plays a crucial role in determining the fracture behaviour of the fresh biomass pellets. This was particularly evident for the mixed wood and eucalyptus pellets, which showed a 38% and 34% lower energy consumption respectively when dried. Despite olive and sunflower pellets having similar moisture contents (~11%), drying resulted in significantly different variations in energy consumption (24% and 8% respectively). The high energy consumption of the fresh pellets is due to the moisture contained within the biomass acting as a plasticising agent (Pierre, Almeida, Huber, Jacquin, & Perré, 2013). This enhances the ductility of the pellets and results in higher milling energy. When dried, the pellets become less ductile, and brake down more easily within the mill. However this plasticising effect is more pronounced in some biomass pellets, which can be traced back to the different pellet process histories and compositions, especially in regard to the strength of the binders holding the pellets together. Steam exploded pellets only showed a 2% reduction in E_e, indicating that the influence of moisture on the fracture behaviour of steam exploded pellets is significantly less pronounced than for non-treated biomasses pellets.

For optimal power plant efficiency, process energy prior to combustion must be minimised. The higher heating value (HHV_d) indicates the potential energy available from a fuel, and the percentage of knife milling energy to HHV_d is listed in Table 2. Overall, milling energy represented a small percentage of HHV_d for the tested samples; sunflower pellets had the lowest fresh and dry ratios (0.31–0.34%), and mixed wood pellets had the highest fresh ratio (0.57%) and olive pellets the highest dry ratio (0.41%). Due to the lower HHV_d of biomass compared to coal (Demirbas, 2004), reducing milling

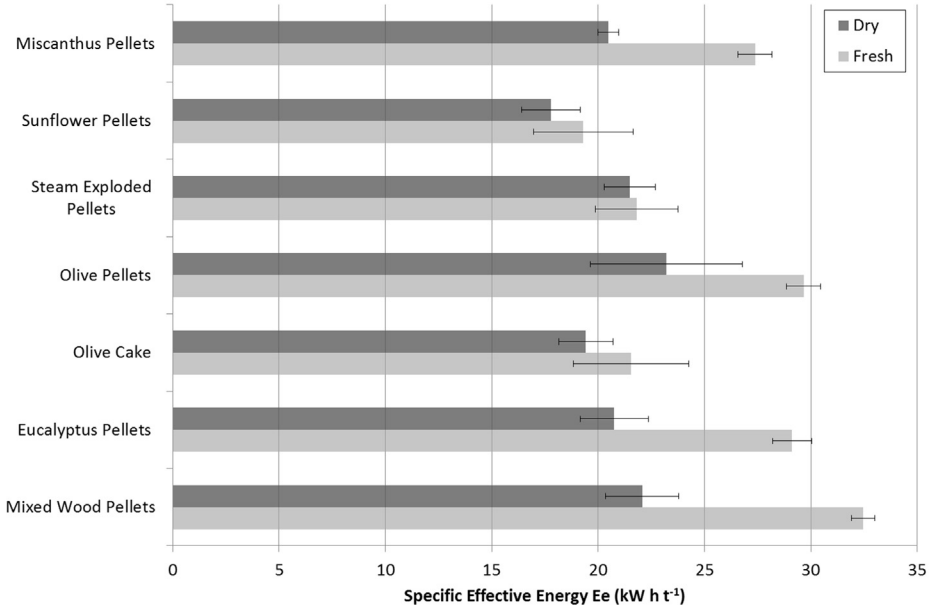

Fig. 1 – Specific effective energy consumption for fresh and dried samples for the Retsch SM300 knife mill. Data are the mean ± the standard deviation of 3 repetitions.

Table 2 – Dry higher heating value (HHV_d), ratio of fresh milling energy to HHV_d, ratio of dry milling energy to HHV_d, energy difference between fresh and dry milling, and moisture evaporation energy for each feedstock. Data are the mean of 3 repetitions.

Sample	HHV_d (MJ kg^{-1})	E_e fresh/HHV_d (%)	E_e dry/HHV_d (%)	Energy difference between fresh and dry ΔE_e (kJ)	Evaporation energy E_{eva} (kJ)
Mixed wood pellets	20.65	0.57	0.39	9.3	53.3
Eucalyptus pellets	20.35	0.52	0.37	7.5	59.1
Olive cake	20.26	0.38	0.35	1.9	89.9
Olive pellets	20.26	0.53	0.42	5.8	63.0
Steam exploded pellets	20.40	0.39	0.38	0.3	40.5
Sunflower pellets	20.76	0.34	0.31	1.4	66.5
Miscanthus pellets	18.67	0.53	0.40	6.2	43.0

energy will have a greater benefit to the overall system efficiency for biomass. However, this saving would need to be greater than the drying energy for it to be of benefit to a power generator.

In situ drying during coal comminution not only increases grindability, but it also reduces mill load, mill wear, and maintenance requirements. A 10% reduction in coal moisture has been demonstrated to provide a 4–12% improvement in boiler efficiency (Akkoyunlu, Erdem, & Pusat, 2016). The evaporation energy for the moisture contained in the fresh biomasses is presented in Table 2. The energy required to evaporate water is much higher (40.5–89.9 kJ) than the energy difference between fresh and dry comminution (0.3–9.3 kJ). This implies that any water released during milling is in the form of water droplets, as the energy difference is not sufficient to evaporate the water from the samples. Coal mills use recycled waste heat to dry the coal (Scott, 1995). Thus, while drying results in an energy penalty, the additional energy required for drying can be minimised by using recycled heat to allow for a net benefit to the entire system.

3.3. *Pellet mechanical durability*

Pellet durability is an indicator of resistance to shocks and abrasion in the fuel handling process. In this study, the pellet durability test was only conducted on fresh samples, and thus it would not be appropriate to correlate the dry energy consumption with the pellet durability results. Figure 2 shows that there is a strong correlation between pellet durability and energy consumption for fresh biomass pellets, a relationship which has not previously been noted in literature. Sunflower pellets had the lowest durability and energy consumption, indicating that the pellets and particles broke down easily in the mill. In contrast, the olive pellets had high energy consumption and highest durability, signifying a strong durable pellet which does not break down easily. This correlation illustrates that pellet construction plays a determining role in the energy required to break down the pellet. However, mixed wood and steam exploded pellets did not fit the trend. This is likely to be related to the high plasticity of the mixed wood pellets resulting in higher energy requirements, while the steam explosion treatment created a more brittle material,

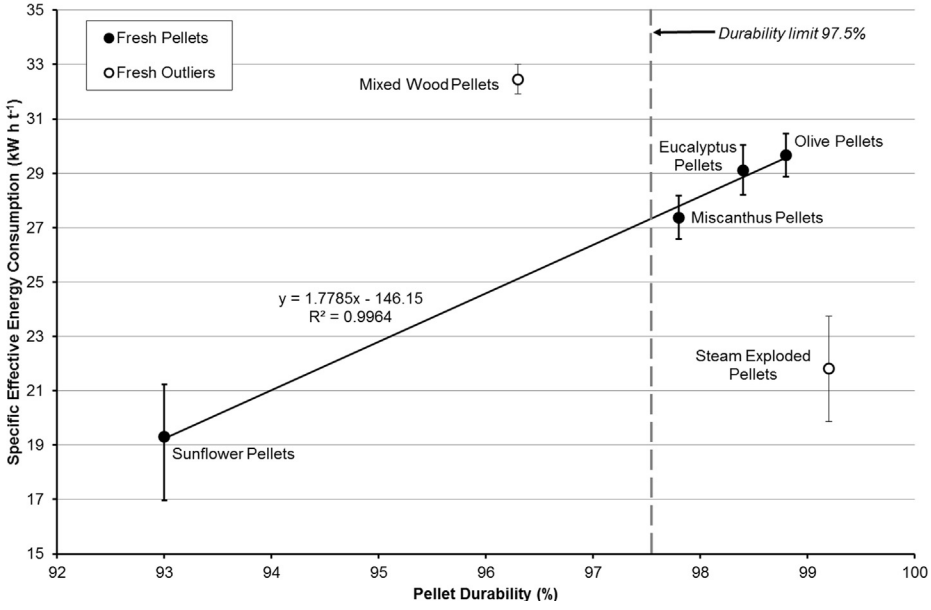

Fig. 2 – Fresh knife mill specific effective energy consumption against pellet durability. The acceptable limits of durability according to BS EN ISO 17225-2/6 for wood and non-wood pellets are noted. Energy data are the mean ± the standard deviation of 3 repetitions and durability data are the mean of 2 repetitions.

which enabled the pellets to break down with little resistance in the mill.

Woody and non-woody biomass pellet specifications for bioenergy have acceptable limits for pellet durability. The lowest pellet durability limits is 97.5% for woody biomass (class A1/A2) and non-woody biomass pellets (class A) (The British Standards Institution, 2014a, 2014b). The optimal biomass pellet for bioenergy must have a balance between durability and milling requirements. The durability of a pellet ensures that the risk of the pellet breaking down and creating dust is minimised, and provides a standardised product which can be easily conveyed in the fuel handling plant. However, the pellet also needs to breakdown easily within the mill to ensure low milling energy and maximise mill throughput. Figure 2 shows that sunflower pellets and mixed wood pellets do not meet this criteria. This has also been noted for other herbaceous pellets produced in laboratory conditions (Carroll & Finnan, 2012).

3.4. *Particle size*

The impact of comminution on particle size is an essential comminution characterisation parameter. For biomass pellets, the impact of particle size reduction is relative to the pre-densified PSD. The combined impact on E_e and PSD can be evaluated by the application of the Von Rittinger theory, which has been successfully used to analyse the comminution of wood pellets in a hammer mill (Temmerman et al., 2013). To obtain the PSD of the pellets prior to milling, the pellets were disintegrated according to BS EN 16126:2012 (The British Standards Institution, 2012). Olive pellets were found to be hydrophobic and thus did not break down during the disintegration test, and no data on the pre-densified PSD was available. Olive cake showed a distinct pre-densified PSD (Table 3 and Fig. 3), as it is a composite of three distinct sections; olive pulp (0–850 μm), olive pips (850–3350 μm) and olive pellets/self-formed lumps (>3350 μm) (Williams et al., 2017). No data was available on the process history of the pellets used in this study. According to BS EN ISO 17225-2 (The British Standards Institution, 2014a), class I1 wood pellets PSD requirements are ≥99% below 3.15 mm, ≥ 95% below <2 mm, and ≥60% below <1 mm. All pellets conformed to the PSD requirements of BS EN ISO 17225-2 apart from the sunflower pellets.

Table 3 lists the size parameters of effective diameter (d_{10}), geometric mean diameter (d_{gw}), Rosin–Rammler characteristic size (d'), and 80th percentile passing particle size (d_{80}) for the pre-densified and milled samples. Fresh and dry comminution resulted in little change in d_{10}. Mixed wood pellets and eucalyptus pellets saw a slight increase in d_{10}, particularly for

Table 3 – Rosin–Rammler particle distribution parameters (characteristic particle size (d'), Rosin–Rammler size distribution parameter (n), distribution fir (R^2)), size parameters (effective particle size (d_{10}), geometric mean diameter (d_{gw}), 80% percentile particle size (d_{80})), dispersion parameters (distribution geometric standard deviation of high (h_s) and low (l_s) regions, mass relative span (MRS), coefficient of uniformity (C_u), coefficient of curvature (C_c)), and distribution shape parameters (inclusive graphic skewness (GS_i), geometric kurtosis (K_g)) for fresh and dried biomass milled in the Retsch SM300 knife mil. Data are the mean of 3 repetitions.

Sample	Rosin–Rammler			Size parameters (μm)			Dispersion parameters					Distribution shape parameters	
	d' (μm)	n	R^2	d_{10}	d_{gw}	d_{80}	h_s	l_s	MRS	C_u	C_c	GS_i	K_g
Eucalyptus pre-densified	833	1.4	1.000	172	631	1215	2.07	2.59	2.10	4.43	1.23	0.31	0.88
Eucalyptus fresh	862	1.6	0.999	199	696	1171	1.81	2.53	1.78	4.15	1.24	0.20	0.89
Eucalyptus dry	919	1.8	0.990	286	696	1222	1.92	2.05	1.84	2.93	0.94	0.37	1.02
Mixed wood pre-densified	966	1.3	0.998	124	744	1373	1.99	3.53	2.12	7.57	1.57	0.22	0.86
Mixed wood fresh	813	1.5	0.999	166	659	1105	1.81	2.71	1.78	4.70	1.35	0.17	0.88
Mixed wood dry	878	1.9	0.993	289	686	1148	1.82	1.99	1.67	2.78	0.99	0.32	1.00
Miscanthus pre-densified	832	1.4	0.992	197	604	1251	2.3	2.33	2.43	3.79	1.08	0.44	1.02
Miscanthus fresh	780	1.5	1.000	164	615	1069	1.87	2.58	1.92	4.48	1.32	0.24	0.95
Miscanthus dry	706	1.4	0.999	137	533	1006	2.09	2.78	2.26	4.72	1.18	0.35	1.06
Olive cake pre-densified	1953	0.9	0.997	194	1303	3660	3.75	4.49	4.11	9.22	1.00	0.58	1.03
Olive cake fresh	1037	1.7	0.999	269	878	1345	1.69	2.52	1.68	3.75	1.05	0.16	0.98
Olive cake dry	835	1.1	0.995	106	627	1356	2.36	4.13	2.52	8.01	0.95	0.35	0.78
Olive pellets fresh	1226	1.5	0.989	255	1004	1517	1.61	2.41	1.53	4.51	1.61	0.05	0.96
Olive pellets dry	897	1.1	0.995	111	720	1372	2.06	4.53	2.18	8.26	1.11	0.22	0.76
Sunflower pre-densified	1115	1.2	0.995	198	774	1744	2.49	2.87	2.70	5.37	1.00	0.45	0.94
Sunflower fresh	848	1.6	0.999	199	690	1145	1.78	2.48	1.70	4.12	1.22	0.17	0.87
Sunflower dry	832	1.5	0.999	179	674	1130	1.80	2.64	1.80	4.49	1.26	0.20	0.94
Steam exploded Pre-densified	889	1.4	0.998	143	724	1196	1.86	3.25	2.06	6.16	1.32	0.19	1.04
Steam exploded fresh	944	1.3	0.995	176	718	1412	2.16	3.15	2.30	5.19	0.97	0.34	0.87
Steam exploded dry	862	1.4	0.995	178	664	1261	2.09	2.89	2.16	4.67	0.95	0.33	0.88

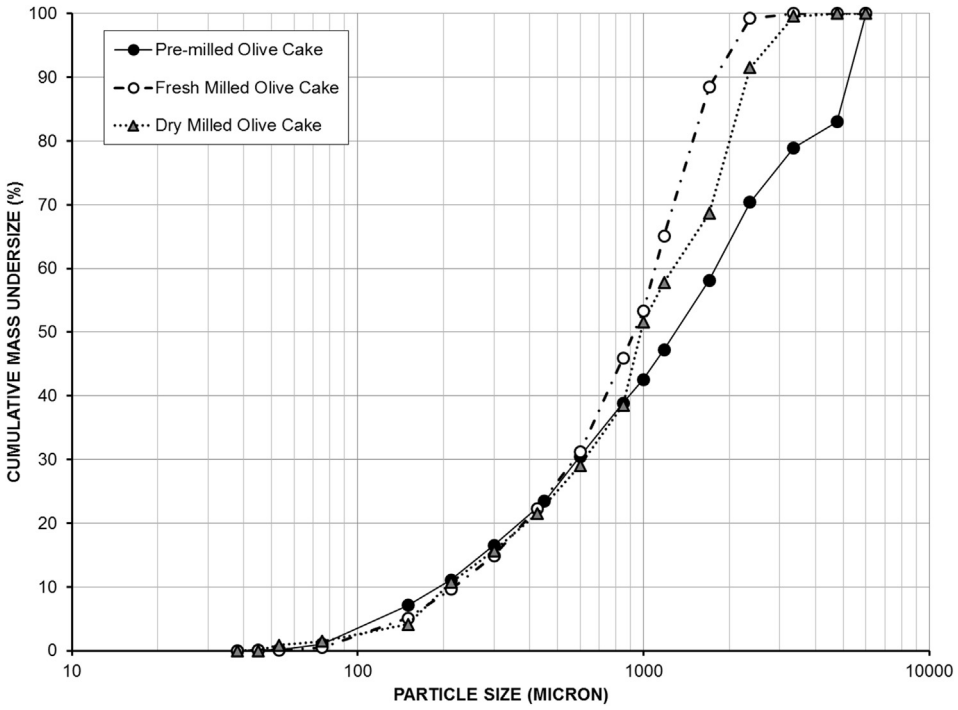

Fig. 3 – Cumulative particle size distributions for pre-densified, and fresh and dried milled olive cake. Data are the mean of 3 repetitions.

dry milling, compared to the pre-densified PSD, which indicates that less fines were produced. Apart from olive cake, most samples d_{gw} and d' reduced by up to 150 μm. The olive cake d_{gw} significantly reduced from 1303 μm pre-densified to 878 μm for fresh milling and 627 μm for dried milling. d_{80} exhibited the largest change of all the size parameters, which reduced by around 200–300 μm for the mixed wood and miscanthus pellets. Olive cake exhibited a significant reduction in d_{80} through milling (3600 μm pre-densified to 1345 μm fresh and 1356 μm dried), as did the sunflower pellets (1744 μm pre-densified to 1145 μm fresh and 1130 μm dry). Olive cake was the only non-densified sample tested in this study, and also showed the largest change in PSD through milling. However, a significant portion of the sample was already below 1 mm (43%), and thus a large portion of the sample was not comminuted. This is reflected in Fig. 3, which shows no real change in the PSD below 700 μm for olive cake. Miscanthus pellets PSD for milled samples was very similar to the disintegrated distribution (Fig. 4), indicating that no real milling of the particles occurred. Steam exploded pellets showed slightly coarser PSD when milled, which suggests that the pellet broke into fragments rather than its constituent particles.

3.5. *Von Rittinger analysis*

Application of Von Rittinger analysis to the results of this study provides a novel insight into the fracture mechanics of biomass pellets. For optimal pellet comminution, it is necessary to ensure that only pellet breakdown occurs, which is indicated by a zero change in particle size (Williams et al., 2015, 2016). This will minimise energy consumption, maximise material throughput, and reduce wear in the mill. Figure 5 illustrates that only fresh and dry steam exploded pellets and dry eucalyptus pellets showed a negative particle size change compared to their pre-densified PSD in this study. All other samples showed a positive size change, indicating that the pre-densified PSD was too coarse to pass through the screen without further comminution.

Further analysis of Fig. 5 indicates that for non-thermally treated pellets, drying resulted in lower energy consumption but did not significantly change the product particle size. This suggests that drying creates a more brittle pellet rather than increasing the brittleness of the constituent particles. This is most notable for the mixed wood pellets whose milling energy was 38% lower when dry comminuted with little impact on the product PSD. This highlights that dry grinding of biomass pellets can result in a significantly lower milling energy without compromising the product PSD.

This also shows that for a diverse range of biomass feedstocks, in general the comminution energy is significantly lower than that of non-densified biomass comminuted in similar knife mills (Miao et al., 2011; Phanphanich & Mani, 2011; Zhang, Song, Deines, Pei, & Wang, 2012), which supports the findings of Temmerman et al. (2013) for wood pellets. The lower milling energy for biomass pellets is due to the different fracture mechanics employed to break down the materials. Wood is an orthotropic material, and has two or three mutually orthogonal two-fold axes of rotational symmetry, resulting in anisotropic mechanical properties (Dinwoodie, 2000). During non-densified biomass comminution, cracks will generally grow along the biomass fibres, irrespective of both the original notch orientation and the mode of fracture (Jernkvist, 2001), giving biomass particles

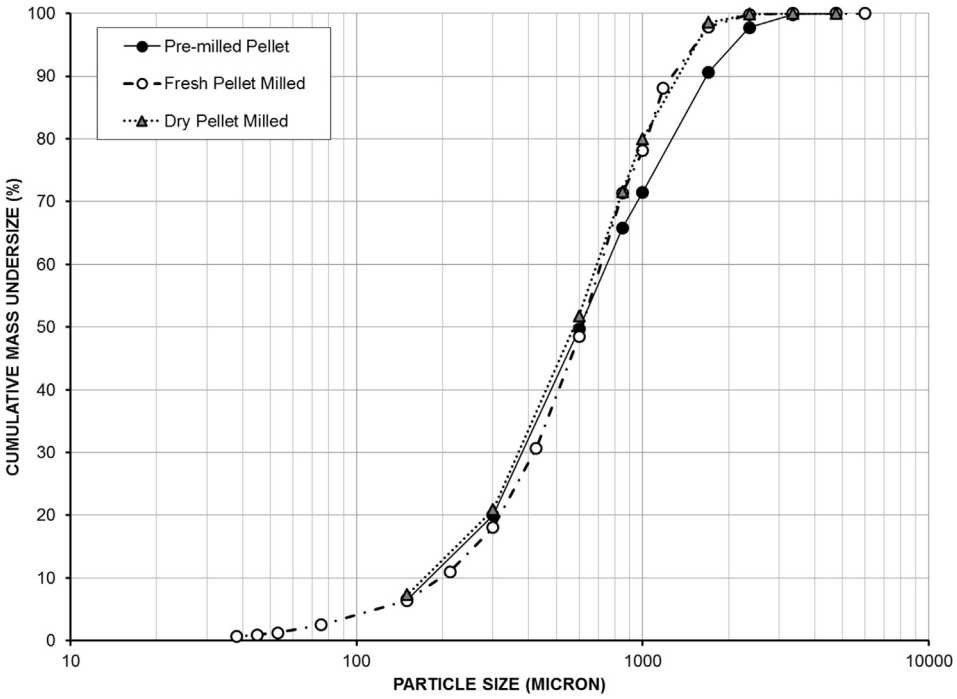

Fig. 4 – Cumulative particle size distributions for pre-densified, and fresh and dried milled miscanthus pellet. Data are the mean of 3 repetitions.

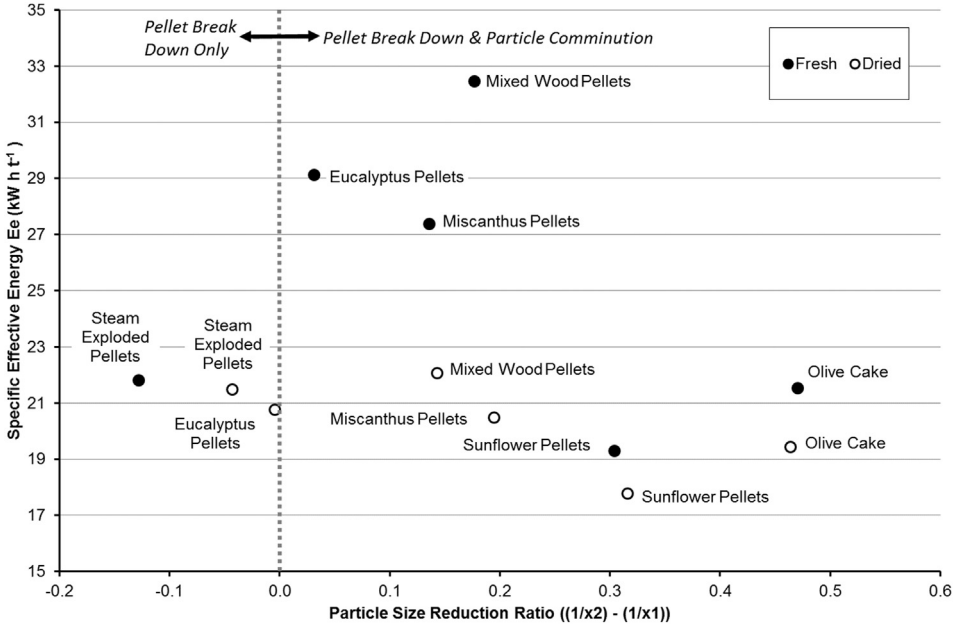

Fig. 5 – Specific effective energy consumption against particle size reduction ratio for the Retsch SM300 knife mill. Data are the mean of 3 repetitions.

their needle like shape. Biomass pellets are formed of comminuted particles which are bound by binders forming solid bridges between particles (Stelte et al., 2011). Ideally biomass pellet comminution should only overcome the weak bonds holding the pellet together and not involve particle comminution, and thus results in lower milling energy than non-densified biomass. However, mill choking can be experienced, and results in significantly higher milling energies which are closer to those of non-densified biomass comminution (Williams et al., 2015).

3.6. *Particle size distribution dispersion and distribution shape analysis*

The statistical evaluation of the PSD profiles provides further insight into the potential benefits of dry grinding. The study

found that there were no discernible trends in PSD dispersion between the fresh and dry grinding trials (Table 3), reinforcing the finding that drying does not significantly change the product PSD properties for a 4 mm screen. Only olive pellets saw notable variance between fresh and dry milling, with dried olive pellets producing a finer and more homogeneous distribution. The biomass pellets saw only slight variances in dispersion by drying, and the impact varied by material type. Apart from fresh olive pellets ($R^2 = 0.989$), all samples showed a good fit of the Rosin–Rammler function ($R^2 > 0.99$), which fits with the results of previous pellet milling studies (Temmerman et al., 2013). Comminution resulted in enhanced uniformity, as indicated by higher the Rosin–Rammler distribution parameter (n). The high graphic geometric deviation (hs) reduced after comminution, indicating a reduction in the coarse size fraction. Only steam exploded pellets saw an increase in hs after milling, increasing from 1.86 to 2.16 for fresh and 2.09 for dry pellets. This is a result of pellet fragmentation during milling rather than pellet breakdown (Fig. 5). The low graphic geometric deviation (ls) illustrated that some pellets such as miscanthus exhibited very little comminution of their fine particles (Fig. 4). The mass relative span (MRS) of above 1 indicates that all samples have a wide distribution, which corroborates with previous studies (Bitra, Womac, Yang, et al., 2009; Gil & Arauzo, 2014; Gil et al., 2012). All the samples apart from the steam exploded pellets, dry eucalyptus pellets and mixed wood pellets, can be considered to be well graded with coefficients of uniformity (C_u) above 4 and a coefficient of curvature (C_c) between 1 and 3.

All the samples exhibited coarsely skewed distributions, with positive inclusive graphic skewness (GSi) and ls being greater than hs (Table 3). As with the dispersion parameters, there were no discernible trends between the fresh and dry grinding, with the impact being material dependent. Non-densified biomass studies have shown positive (Bitra, Womac, Yang, et al., 2009) and negative GSi values (Gil & Arauzo, 2014; Gil et al., 2012), but no values are available for comparison for biomass pellets in literature. In general, the geometric kurtosis (k_g) of the PSD was close to 1 for most samples, indicating that the PSD were well sorted and close to a normal Gaussian distribution, which matches with non-densified biomass comminution studies (Bitra, Womac, Yang, et al., 2009). Most samples had platykurtic curves ($k_g < 1$) after milling with a few samples such as dried miscanthus and eucalyptus pellets having leptokurtic curve ($k_g > 1$).

3.7. Particle shape

In a previous study by the authors (Williams et al., 2016), it was found that biomass particle shape was not significantly influenced by comminution, even when a large particle size reduction was observed. This study builds upon this finding by establishing the impact of drying on particle shape factors. Table 4 summarises the mean sphericity, circularity, symmetry, and aspect ratio for the pre-densified and milled samples. Shape factor values increase as the feed stock moves from herbaceous and wood to thermally treated and olive cake. As with the PSD parameters, the changes in shape factors were material dependent. Miscanthus pellets had the lowest mean pre-densified sphericity (0.353), followed by sunflower (0.375), mixed wood (0.376), eucalyptus (0.432), steam exploded pellets (0.458), and olive cake (0.584) having the highest mean sphericity.

Apart from olive cake, all samples experienced an increase in particle sphericity and aspect ratio through milling. The reduction in olive cake sphericity is potentially due to the influence of the square screen shape on the comminuted product. For circularity and symmetry, much lower levels of change were observed through milling. All samples were asymmetric in nature ($Symm$ <1), with the centre of the area within the particle ($Symm$ >0.5). There was little difference in

Table 4 – Impact of drying on average particle sphericity (φ), circularity (C), symmetry ($Symm$) and aspect ratio (AR) for biomass milled in the Retsch SM300 knife mill. Data are the mean of 3 repetitions.

Sample	Average sphericity (φ)	Average circularity (C)	Average symmetry ($Symm$)	Average aspect ratio (AR)
Eucalyptus pre-densified	0.432	0.545	0.745	0.544
Eucalyptus fresh	0.441	0.543	0.772	0.553
Eucalyptus dry	0.449	0.550	0.735	0.560
Mixed wood pre-densified	0.376	0.492	0.781	0.484
Mixed wood fresh	0.413	0.494	0.765	0.526
Mixed wood dry	0.405	0.539	0.765	0.515
Miscanthus pre-densified	0.353	0.508	0.796	0.455
Miscanthus fresh	0.384	0.486	0.754	0.492
Miscanthus dry	0.396	0.482	0.739	0.502
Olive cake pre-densified	0.584	0.757	0.863	0.692
Olive cake fresh	0.560	0.742	0.851	0.673
Olive cake dry	0.565	0.719	0.834	0.676
Olive pellets fresh	0.551	0.724	0.844	0.665
Olive pellets dry	0.546	0.700	0.800	0.659
Sunflower pre-densified	0.375	0.567	0.797	0.481
Sunflower fresh	0.426	0.525	0.771	0.539
Sunflower dry	0.432	0.575	0.794	0.545
Steam exploded Pre-densified	0.458	0.62	0.816	0.577
Steam exploded fresh	0.498	0.648	0.821	0.615
Steam exploded dry	0.487	0.662	0.821	0.605

the herbaceous and wood pellets circularity and symmetry values through comminution. Only olive cake, olive pellets and steam exploded pellets showed significant change in values. The limited impact of drying and comminution on the shape factors of several samples is significant when related to the Von Rittinger analysis (Fig. 5). The steam exploded pellets show a noticeable change in shape factors through comminution, but exhibited a negative particle size change, which is due to the fragmentation of the pellets. Olive cake exhibited the largest particle size reduction and change in shape factors, indicating significant comminution of the particles took place. Apart from eucalyptus pellets, all other samples experienced positive sized reductions with minimal changes in shape factor. This is potentially due to the same fracture mechanism being employed in the pre-densification and pellet comminution processes.

3.8. *Implications of study for industrial bioenergy applications*

This study has highlighted several important considerations for biomass pellet comminution for pulverised fuel power generation systems. While converted coal mills maintain their drying section for biomass comminution, hammer mills do not include a drying section. The moisture content of biomass has been shown to cause an ignition delay in pulverised biomass particles, with higher moisture contents significantly increasing this ignition delay (Mason, Darvell, Jones, Pourkashanian, & Williams, 2015). Given that dry comminution of coal is also known to increase boiler efficiency and reduce mill wear and maintenance rates (Akkoyunlu et al., 2016), there is a strong case for employing dry comminution for biomass pellets. This study has shown that dry comminution of biomass pellets results in enhanced product quality. Particularly for wood pellets, drying results in significantly lower milling energy without compromising the product particle size and shape. While the difference in milling energy between fresh and dry comminution is less than that required to dry the biomass pellets, this energy demand can be reduce by using measure such as waste heat recycling. Additionally, hammer mills experience high hammer wear rates, which results in high consumable costs and significant periods of system downtime. Drying results in more brittle pellet, and optimising the pellet PSD to ensure that only pellet breakdown occurs would allow for maximised material throughput and minimal milling energy, and potentially reduce mill wear and maintenance issues.

4. Conclusions

Fresh and dry comminution was compared for a diverse range of biomass feedstocks in a knife mill. Milling energy consumption was found to be significantly lower than that reported in literature for non-densified biomass in similar knife mills (19.3–32.5 kW h t^{-1} [fresh] and 17.8–23.2 kW h t^{-1} [dry]). The impact of drying was found to vary by feedstock. Dry milling energy was 38% lower for mixed wood pellets, but only 2% for steam exploded pellets. Milling represents only a small percentage of the samples' higher heating values (0.34–0.57% fresh), and drying further reduced this percentage (0.31–0.42%). The energy required to dry the biomass pellets is greater than that saved by in comminution through dry grinding. However, dry comminution needs to be considered from a whole system perspective due to its additional system wide benefits. A strong correlation was found between pellet durability and knife mill energy consumption for fresh biomass pellets. Thus, pellet construction plays a key role in determining the energy required to break down a pellet into its constituent particles. A greater understanding is required between milling and pellet durability and its relation to pellet process history.

Variations in feedstock and pellet composition were found to be more influential on particle size and shape than dry grinding. Only the steam exploded pellets and dry eucalyptus pellets showed a negative or zero particle size change. All other samples experienced pellet break down and particle comminution, but also very little change in shape factors. The study also highlighted that dry comminution has the potential to significantly reduce energy consumption without compromising the product PSD for a 4 mm screen.

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council [grant number EP/G037345/1] (EPSRC). This research is also funded and supported by the Biomass & Fossil Fuel Research Alliance (BF2RA) and EDF Energy plc. The study was part of an Engineering Doctorate at the Efficient Fossil Energy Technology Centre in the Faculty of Engineering at The University of Nottingham. The authors would like to thank all those involved for their support and cooperation during the course of the research.

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