Applied Energy 182 (2016) 219–231

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Influence of mill type on densified biomass comminution

Orla Williams [a,*], Gary Newbolt [a], Carol Eastwick [a], Sam Kingman [a], Donald Giddings [a], Stephen Lormor [b], Edward Lester [a]

[a] Faculty of Engineering, The University of Nottingham, University Park, Nottingham NG7 2RD, UK
[b] Engineering Team, EDF Energy plc., Cottam Power Station, Outgang Lane, Retford DN22 0EU, UK

HIGHLIGHTS

- Comminution of wide range of densified biomass in four mills.
- Shape factors do not change significantly compared to particle size with milling.
- Shape will only noticeably change below the critical particle size for comminution.
- Mill choking linked to the particle size, shape and classifier Stokes condition.
- Classification requirements should inform biomass pellet particle sizes.

ARTICLE INFO

Article history:
Received 13 April 2016
Received in revised form 17 August 2016
Accepted 18 August 2016
Available online 28 August 2016

Keywords:
Biomass
Stokes condition
Milling
Mill choking
Particle size
Particle shape

ABSTRACT

The impact of different mill fracture mechanisms were examined for a wide range of densified biomass pellets to provide a comprehensive analysis of biomass milling behaviour for pulverised fuel combustion. The milling behaviour of 7 woody, herbaceous, fruit, and thermally treated densified biomasses were investigated for four distinct types of comminution fracture mechanism using traditional milling indices and novel application of 3D imaging techniques. For the coal mill trials, a reference coal was used to provide a milling performance comparator. For the pre-milled samples, woody and herbaceous pellets have the least spherical particles (φ 0.324–0.404), followed by thermally treated pellets (φ 0.428), La Loma coal (φ 0.503), with olive cake having the most spherical particles (φ 0.562). This trend was noted for all the shape factors. Conventional comminution did not significantly impact biomass particle shape, even after a significant change in particle size. Therefore biomass pellet process history plays a key role in determining the comminuted particle shape. La Loma coal had significantly enhanced milling performance in comparison to the biomasses in the coal mills. Significant improvements in grindability and shape factors were observed for the thermally treated pellets. Mill choking was experienced for several of the woody and herbaceous samples, which resulted in a significant energy penalty. The mechanisms of mill choking were found to be intrinsically linked to the critical particle size of comminution through compression, particle shape factors, and the Stokes conditions set for the classifier and burners in pulverised fuel combustion systems. The study showed that for optimal milling performance, biomass pellets should be composed of particles which meet the Stokes requirements of the mill classifier. This would minimise the potential for mill choking and milling energy penalties, and ensure maximum mill throughput.

1. Introduction

Biomass is the biggest source of renewable energy in the EU and is expected to make a significant contribution to the 20% EU renewable energy target by 2020 [1]. Biomass conversion and co-combustion in coal fired power stations offers a low cost and high impact solution to reducing carbon emissions. However technical issues with using biomass in existing coal mills has led to mill blockages, fires, and reductions in boiler thermal output [2]. Biomass particle shape data is crucial in mill classifier and burner design and optimization [3], but there is only limited experimental data available in literature [4]. In this study, the impact of different mill fracture mechanisms on a wide range of different densified biomass pellets used for pulverised fuel combustion were examined in order to provide a comprehensive analysis of biomass milling behaviour.

* Corresponding author.
E-mail address: ezzow@nottingham.ac.uk (O. Williams).

http://dx.doi.org/10.1016/j.apenergy.2016.08.111
0306-2619/© 2016 The Authors. Published by Elsevier Ltd.

Nomenclature

a	diameter of a circumscribed sphere around a particle (μm)
AR	particle aspect ratio (dimensionless)
C	circularity of a particle (dimensionless)
d	diameter of a sphere of the same volume as a particle (μm)
d'	Rosin-Rammler characteristic particle size (μm)
d_1	feed particle size (d_{80}) (μm)
d_2	product particle size (d_{80}) (μm)
d_{80}	particle size at 80th percentile of cumulative distribution (μm)
d_A	area equivalent diameter of a particle (μm)
d_P	perimeter equivalent diameter of a particle (μm)
d_{c_min}	shortest chord diameter (μm)
d_{Fe_max}	maximum Feret diameter (μm)
E_e	total effective specific energy (kW h/t)
HHV	higher heating value (J/g)
HHV_d	dry higher heating value (J/g)
K	Von Rittinger constant (dimensionless)
M	moisture content (%)
m	mass of sample in milling tests (g)
n	Rosin-Rammler size distribution parameter (dimensionless)
P	instantaneous power consumption (kW)
P_i	average idle power consumption (kW)
$R(d)$	Rosin-Rammler cumulative percentage undersize mass (%)
r_1 and r_2	distance from the centre of area of the borders in measuring direction (μm)
$Symm$	symmetry of a particle (dimensionless)
t	time (s)
φ	sphericity of a particle (dimensionless)

Legislation to reduce Nitrogen Oxide (NO_x) emissions in coal fired power stations has led to improvements in combustion efficiency through the introduction of low NO_x burners and improved fineness of coal particles [5]. The size of particles reaching the burner is dictated by the comminution equipment. Coal mills use static or dynamic pneumatic classifiers to select the correct cut size and consistency for combustion. For coal, the industry standard cut size for a classifier is that 75% of coal delivered to the burner must pass a 200 mesh screen (75 μm) [6], and for biomass the standard classifier setting is 1 mm [7]. Mill classifiers separate particles by using the Stokes condition based on the cut size [8]. The Stokes condition is a measure of the ability of particles to follow the surrounding flow [9], however it assumes spherical particles and thus shape factors need to be introduced for nonspherical particles. True sphericity was defined by Wadell [10] as the ratio of surface area of a sphere with the same volume as a particle to its actual surface area. As noted by Krumbein and Sloss [11], the measurement of true sphericity of an irregular particle is not feasible. Wadell [12] proposed a more practical definition of sphericity called Operational Sphericity (φ), which Krumbein and Sloss [11] defined as:

$$\varphi = \frac{d}{a} \tag{1}$$

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. As the Stokes condition is also dependent on a particle's Reynolds number; it is possible for large biomass particles to have similar aerodynamic properties to that of a much smaller coal particle provided they have a sufficiently low sphericity [13]. At present, solid fuel combustion prediction models rely on a spherical particle shape assumption [14], which may deviate from reality for large biomass particles [3]. Shape data is based on simplified shape assumptions of biomass shape, which is usually obtained from imaging [4]. Several studies have analysed the 2D shape factors of biomass through microscopy [15], 2D digital imaging [16–18], and 3D particle reconstruction algorithms have been developed to calculate sawdust particle surface area and volume [19]. However all these studies used small representative particle sizes, and there is no reported experimental data on the operational sphericity of comminuted biomass particles for large sample sizes.

In order to improve the bulk density for transportation, biomass is often milled to a coarse particle size then pelletized [20]. For the production of biomass pellets, feed stocks need to be comminuted so that at least 97% of the particles making up the pellet are below 3.35 mm in size [21]. Biomass milling studies have largely focused on non-densified woody, herbaceous, and agricultural residue biomasses in hammer and knife mills [7,18,22–37]. There are very few studies which consider the milling of densified biomass [38–41]. Planetary ball mills have been used to assess the improvement in grindability of torrefied biomasses through modified Hardgrove Grindability Index (HGI) tests [42,43], and used to develop hybrid work indices for torrefied materials [44]. There are limited accounts of biomass milling trials for coal mills in literature [41,45]. Studies tend to focus on standard coal grindability tests such as HGI [46,47] or Bond Work Index (BWI) test [39]. Very few studies compare the milling behaviour of different biomasses in different mills. Studies are generally limited to one biomass group such as woods in several types of mills [41], woods in a range of hammer mills [48], or herbaceous biomasses in a range of knife mills [31]. There are even fewer studies which look at the impact of milling on biomass shape factors. Torrefaction has been shown to improve biomass 2D shape factors [18], and reduce the agglomeration phenomenon characteristics of smaller particles of pulverised biomass, which leads to enhanced operation of pulverised biomass into boilers [49].

The aim of this study was to quantify the impact of different mill types commonly used in power generation on the milling behaviour and physical characteristics of several densified biomasses. This is the first study which investigates and compares the milling behaviour of woody, herbaceous, fruit, and thermally treated densified biomasses, along with a reference coal for the two coal mill tests, using four distinct types of comminution fracture mechanism. In addition, for the first time the impact of different milling operations on the operational sphericity of biomass particles has been assessed, and the paper demonstrates how this relates to the conditions used to select particles for combustion in full scale mills, particularly in relation to common mill operation issues such as mill choking, and the process history of the biomass pellets.

2. Materials and methods

2.1. Materials & pre-milling characterisation

The samples used (Fig. 1) are either routinely co-fired in coal fired power plants or have been used in biomass combustion trials. Portuguese mixed wood pellets (mainly pine (*Pinus*) with eucalyptus (*Eucalyptus grandis*)), Spanish olive cake (*Olea europaea*) - a residual waste mix from olive oil production, Russian sunflower