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Secondary comminution of wood pellets in power plant and laboratory-scale mills

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Abstract

This study aims to determine the influence of mill type and pellet wood composition on particle size and shape of milled wood. The size and shape characteristics of pellets comminuted using power plant-scale roller- and hammer mills were compared with those obtained by using a laboratory-scale roller mill. A 2D dynamic imaging device was used for particle characterization. It was shown that mill type has a significant impact on particle size but an almost negligible effect on the shape of milled wood. Comminution in the pilot plant using a Loesche roller mill requires less energy than using a hammer mill, but generates a larger fraction of coarse particles. The laboratory-scale roller mill provides comparable results with the power plant roller mill with respect to particle size and shape.

Keywords: pellets, hammer mill, roller mill, particle size, shape

Nomenclature

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A	Particle area (m^2)	q_3	Frequency particle distribu-
AR	Aspect ratio		tion, based on volume (% \rm{mm}^{-1})
A_{conve}	$_x$ Particle convex area (m ²)		,
A_{real}	Particle projection area (m^2)	r_1, r_2	Distances from the area center to the particle edges (m)
b	Particle width (m)	SPH	T Circularity (Sphericity)
Conv	Convexity		
d	Diameter (m)	Symn	<i>n</i> Symmetry
l	Particle length (m)	V	Volume (m ³)
m	Number of size classes	$x_{Fe,ma}$	$_{ux}$ Feret maximum diameter (m)
Р	Perimeter of a particle projec-		
	tion (m)	$x_{Ma,m}$	$_{in}$ Martin minimum diameter
$\overline{q_3}$	Histogram (% mm ⁻¹)		(m)
Q_3	Cumulative particle distribu-	Subse	cripts
	tion, based on volume ($\%$	i	Number of the size class with
	mm^{-1})		upper limit \mathbf{x}_i

1. Introduction

Biomass firing is used for power generation and is considered as an important step in the reduction of greenhouse gas emissions. The anthropogenic CO₂ emissions can be decreased by the substitution of biomass in pulverized combustion due to the lower regeneration time of biomass compared to bitu⁵ minous coal. Thus, CO₂ released using biofuels will be reconsumed faster by ⁶ other plants via photosynthesis than the time needed to regenerate coal. The ⁷ milling process is a necessary step in suspension fuel firing [1]. Size reduction ⁸ improves conversion processes due to the creation of larger reactive surface ⁹ areas [2, 3]. Biomass is due to its fibrous structure difficult to mill. An in-¹⁰ creased energy input into biomass comminution affects the total efficiency of ¹¹ power plants, and often causes problems with flame stability and burnout ¹² when large particles remain after milling.

The common method for preparing biomass for suspension firing is to 13 pelletize lignocellulosic materials, and then pulverize the biomass pellets us-14 ing coal roller mills [4]. A number of studies [3, 5-10] have investigated the 15 influence of mill type on both the particle size and shape. Momeni [5] showed 16 that comminuting woody pellets in hammer and roller mills produced signif-17 icantly different sized particles. In other investigations [6, 8], higher fractions 18 of fine particles were obtained after comminution in a hammer mill compared 19 to milling using a knife mill. In agreement with this observation, the energy 20 consumption of the knife mill was found in all cases to be smaller than that 21 of the hammer mill [7, 8]. The feedstock type (hardwood, straw, corn cobs 22 and corn stover) affected the energy consumption of the hammer and disk 23 mills [9]. The energy consumption for the comminution of dry pellets was 24 lower for the hammer mill than for the disk mill, and the particle size dis-25 tribution was broader with larger particle aspect ratios after comminution 26 in the hammer mill [10]. In addition, it was reported that a high moisture 27 content (> 20 %) increased the specific energy consumption by 50 % [10]. It 28 appeared that different feedstocks (switchgrass, corn and soybean) showed 29

differences in the particle size and shape during comminution and generated 30 particles with various morphological properties [11]. Previous investigations 31 of biomass comminution demonstrate disagreements in terms of the effect 32 that mill and feedstock type have on particle shape. Bond [12] and Hey-33 wood [13] reported that fuel type has a stronger influence on the particle 34 shape than mill type, whereas Rose [14] showed that mill type mainly affects 35 particle shape. Generally, little is known about the effect of mill type on 36 particle shape and size when lignocellulosic materials are milled. 37

In this study, the impacts of mill and feedstock type on particle size and shape were investigated. Wood pellets are comminuted using a laboratoryscale roller mill, a laboratory-scale hammer mill, and power plant-scale Loesche roller mills. Particle size and shape of milled pellets were characterized using sieving and 2D dynamic imaging analysis. The objective of this study was to gain knowledge concerning the impact of mill type, fuel type, and pelletization method on both particle size and shape of milled biomass.

45 2. Materials and methods

Raw pellets, without additives or binding agents, were provided by the 46 companies LatGran (Latvia) and Heatlets (Estonia). The pellets were pro-47 duced in the process shown in Figure 1. Wood logs with diameters of 5-60 cm 48 and length of 3-4 m were initially dried, and then shredded in a mobile shred-49 der to 8-45 mm. The primary comminution includes the milling of wood chips 50 to the particle size of 0.5-2 mm in diameter and 1 cm in length by a knife ring 51 flaker and a drop feed chipper, and sawdust milling in a hammer mill to ob-52 tain a homogeneous and fine material below 1.5 mm in size. The sawdust 53

⁵⁴ before being pelletized, contained 75% particles following the process de⁵⁵ scribed in Figure 1 and contained 25% coarse bark sawdust residues from
⁵⁶ comminution on a disk mill.

The pellets were produced using ring die pellet machines in which a die ring runs around fixed rollers [15]. The sawdust was added to the roller sideways and pressed through the holes of the die. The string of pressed material leaving the die was broken off into 22 mm long pellets, and then the pellets were cooled down from 90°C to room temperature for stabilization and hardening. 1. Wood logs (5-60 cm width, 3-4 m length) 2. Chips (8-45 mm)



Pelletizing machine

6

Figure 1: Wood pellets production from (1) Wood logs to (2) Chips, (3a) Sawdust combined with (3b) Coarse sawdust from bark and to (4) Pellets.

The pellets were transported to three power plants including Hern-63 ingsværket (HEV), Avedøreværket (AVV) operated by DONG Energy A/S, 64 and Amagerværket (AMV) operated by HOFOR A/S (formally Vattenfall 65 A/S). Secondary comminution was then carried out either in the hammer 66 (HEV) or in the horizontal Loesche roller mills (AMV and AVV). Pulver-67 ized wood was sampled from the pipeline (running to the burners) through a 68 side opening by using a vacuum cleaner or a rotorprobe. The pellets under-69 went additional milling in the laboratory-scale roller mill at TU Clausthal. 70 The particle size and shape of the milled pellets were characterized by light 71 microscopy, scanning electron microscopy (SEM), sieving and 2D dynamic 72 imaging. 73

74 3. Particle size and shape characterization

Light microscopy. Light microscopy of sawdust and disintegrated pellets was
conducted using a Microscope Heating Stage 1750 (Leica Microsystems, Germany) in order to characterize the particle shape.

SEM microscopy. SEM analysis of milled pellets was conducted using an
Inspect microscope (FEI Company, USA) with a tungsten filament under
high vacuum in order to obtain information on char structural properties.
Prior to the analysis, milled pellet samples were coated with a thin layer of
carbon (40 s, 5 mA) using a Carbon Coater 208 (Cressington, Germany) to
avoid sample charging.

Sample preparation. Prior to the particle size and shape analysis, biomass
samples were divided into four equal 100 mg fractions using a micro-riffler

⁸⁶ PT100 (Retsch Technology, Germany).

Sieving. A vibrating sieve shaker AS 200 (Retsch Technology, Germany) 87 comprising seven sieves ranging from 0.25 to $4 \,\mathrm{mm}$ in opening size and a 88 bottom pan ($< 0.25 \,\mathrm{mm}$) was used. The sieving analysis is described in 89 EN ISO 17827-2:2016. Particles remaining on each sieve and in a bottom 90 pan were collected and weighed using an electronic top pan balance $(\pm 0.01 \text{ g})$ 91 accuracy). The cumulative retained undersize is the mass passed from the 92 previous sieve minus the mass retained on the current sieve [16]. Sieving was 93 conducted for $15 \min \text{ at } 3 \min \text{ amplitude } [17]$. 94

2D dynamic imaging analysis. The particle size and shape were measured 95 using the CAMSIZER (Retsch Technology, Germany), designed for particles 96 ranging from 0.03 to 30 mm in size. Particle shadows were captured by two 97 cameras; a zoom camera, designed for the analysis of smaller particles, and a 98 basic-camera that was able to detect larger particles. The projected area of gc the particle was determined using the CAMSIZER 6.3.10 software (Retsch 100 Technology, Germany). The particle size distribution, based on volume, is 101 represented by the $x_{Ma,min}$ diameter. For the particle size analysis, ca. 100 mg 102 of a dry sample was used. 103

The Martin minimal $(\mathbf{x}_{Ma,min})$ and Feret maximal $(\mathbf{x}_{Fe,max})$ diameters are suitable parameters to represent the biomass particle width and length. The Martin diameter is a characteristic length that divides the projected particle area into two equal halves [18], as shown in Figure S-1.1 of the supplemental material. The minimal Martin diameter $(\mathbf{x}_{Ma,min})$ is determined from the smallest Martin diameter of the particle projection [19]. The Feret diameter is the distance between two tangents placed perpendicular to the
measurement direction [18], as shown in Figure S-1.2. The Feret maximal
diameter is the longest Feret diameter of all measured Feret diameters of a
particle [19].

In the present study, particle shape is characterized by both the sphericity (SPHT) and the aspect ratio (AR). Sphericity is one of the most commonly used parameters to express the deviation of a two-dimensional particle image from a sphere and is defined as

$$SPHT = \frac{4 * \pi * A}{P^2} \tag{1}$$

where P and A are the measured perimeter and area of a particle projection. A particle is considered to be spherical when the value of sphericity is equal to 1 and non-spherical when it is less than 1. The aspect ratio is defined as the ratio of particle width ($b = x_{Ma,min}$) to the particle length ($l = x_{Fe,max}$) so that

$$AR = \frac{b}{l} \tag{2}$$

¹²³ Convexity (Conv) is defined as the square root of the ratio of the real area ¹²⁴ of a particle projection area (A_{real}) to the convex area (A_{convex}) so that

$$Conv = \sqrt{\frac{A_{real}}{A_{convex}}} \tag{3}$$



Figure 2: Definition of convexity.

¹²⁵ Particle symmetry (Symm) is defined as

$$Symm = \frac{1}{2} \left(1 + \left(min\frac{r_1}{r_2} \right) \right) \tag{4}$$

where r_1 and r_2 are distances from the area center to the particle edges 126 on the same line. The center of area (C) in Figure 3 is determined by the 127 CAMSIZER software. Many lines are drawn in such a way that each line 128 passes through the center of area from particle edge to edge. The symmetry 129 is calculated from the smallest ratio of the resulting segments $(r_1 \text{ and } r_2)$. 130 For highly symmetrical particles like circles, ellipses or squares the value 131 for symmetry nears one. The center point divides each line in two parts. 132 The symmetry is equal to 0.5, if the center of the area is exactly at the 133 particle border. For asymmetrical particles i.e. broken beads, triangles, the 134 symmetry is less than one. The symmetry varies from 0 to 0.5 and r_1 and r_2 135 overlap, if the center of area is outside of a particle so that 136

$$\frac{r_1}{r_2} < 0 \tag{5}$$



Figure 3: Definition of symmetry.

Particle size distribution. The results are presented as a cumulative particle
size distribution, based on volume. The cumulative particle size distribution
is described in EN ISO 9276-1:1998, and is defined as

$$Q_3(x_{Ma,min,m}) = \sum_{i=1}^m \overline{q_3}(x_{Ma,min,i}) \Delta x_{Ma,min,i}$$
(6)

where $\overline{q_3}$ is the area beneath the histogram. The results of a particle size analysis were also presented as a frequency distribution over $x_{Ma,min}$, based on volume (q₃), so that

$$q_3(x_{Ma,min}) = \frac{dQ_3(x_{Ma,min})}{dx_{Ma,min}} \tag{7}$$

The particle size distributions obtained from sieving and 2D dynamic imaging 143 were defined based on three sizes within the entire population: d10, d50, 144 d90. The d50 value is the median particle size within the population, with 145 50% of the population greater than this size, and 50% smaller than this 146 size. Similarly, 10% of the population is smaller than the d10 size; while 147 90% of the population is smaller than the d90 size [20]. All measurements 148 were conducted in triplicate to establish repeatability which was better than 149 95%, as shown in the supplemental material. The measurement inaccuracy 150 in sieving analysis was mainly caused by weighing errors. 151

¹⁵² 4. Mills and sampling

Mills of varying size were used in this study and are presented below in order from largest to smallest mill in terms of throughput.

Power plant-scale roller mill. The horizontal LM 19.2 D roller mills (Loesche GmbH, Germany) are used for comminution of wood pellets at AMV. Larger LM 23.2 D roller mills are operated at AVV. A horizontal roller mill comprises of 2-6 conical rollers which are hydraulically pressed onto a horizontal rollar rotating grinding table [21]. The roller axis is inclined at 15° to the table, and the axes of the rollers and table do not intersect, as shown in Figure 4.



Figure 4: A schematic representation of a power plant-scale roller mill [21–23].

Feedstock is directed onto the center of the table and is thrown outward by rotation under the rollers and into a rising air flow at the periphery which is directed by means of a louvre ring that surrounds the grinding table and conveys the air flow to the classifier. Fine fuel particles pass with the air flow through an integral rotary classifier, whereas coarse fuel particles remain on the feed table [21]. Throughput of the horizontal roller mills is up to 70 t h^{-1} .

Laboratory-scale hammer mill. In this study, Andritz 650-450 hammer mill
 (Andritz GmbH, Germany) was used. A hammer mill consists of hammers

installed on a rotating disk which is enclosed within a liner [24]. Feedstock
is drawn into the mill, and ground by the impact between hammers and the
wall, as shown in Figure 5.



Figure 5: A schematic representation of a hammer mill [24].

The speed of the hammers produces kinetic energy that is dissipated on the material, leading to its disintegration. Feedstock is hammered until it is small enough to pass through the screen, and then is removed by shovels, augers, or a chain elevator [25]. The hammer mill at HEV has a drum diameter of 650 mm and a drum length of 450 mm with four hammer shafts (fifteen hammers per shaft). Throughput of the mill is up to 10 t h^{-1} . Laboratory-scale roller mill. A laboratory-scale roller mill at TU Clausthal
was applied in this study, which is designed as a roller table mill with a single
roller. A sketch [26] of the roller mill at TU Clausthal is shown in Figure 6:



Figure 6: A schematic representation of a laboratory-scale roller mill at TU Clausthal [26].

The grinding table is circular and driven by an electrical motor. The conical grinding roller is placed over the grinding table and mounted at the lever system with a spring. The adjustable stop limits the lever's movement to avoid contact between the roller and the table. The feeding system, consisting of a funnel and shaft, is mounted opposite to the roller. The distance between the table bottom and the shaft outlet can be varied to control the

feeding rate. The tube positioned behind the roller serves to discharge the 187 lignocellulosic materials. The mill is equipped with transducers for adjusting 188 the torque, the grinding force and the gap between the roller and the table 189 bottom [26]. The table diameter is 150 mm and the width is 42 mm, the mid-190 dle roller diameter is 100 mm with a roller width of 40 mm. The maximal 191 roller inclination is 15°, the maximal motor power is 5.5 kW, and table rev-192 olutions vary from 5 to 150 min^{-1} . Throughput of the laboratory-scale roller 193 mill is between 11 and 14.7 kg h^{-1} . 194

Rotorprobe sampling method. The material, comminuted in both the laboratoryand the power plant-scale mills, was sampled from the mills exit tubes using
a rotorprobe and a vacuum cleaner. The rotorprobe method is described in
EN ISO 9931:1991. Samples were extracted using a sampling probe consisting of four nozzles; each nozzle extracts from an equally sized area of the
pipeline to ensure uniform collection.

Vacuum cleaner sampling method. A vacuum cleaner entrains pulverized material from a pipeline, which supplies fuel to the burners. A vacuum cleaner
hose was placed perpendicular to the direction of flow. The principle of the
vacuum cleaner sampling is shown in Figure 7.



Figure 7: Vacuum cleaner sampling method: (1) vacuum cleaner, (2) particles flow in the pipe, (3) sector of flow before and after sampling and (4) sampling sector.

Filtering. In hammer mills, air is drawn at the top of the mill to cool the mill components and draw the milled material through the screens into the outlet hopper. The air and fine fuel particles are drawn to the air exhaust via a bag filter. The remaining coarse material is collected at the bottom of the outlet hopper. Both coarse and fine fractions are discharged from the mill using screw feeders.

Pellets. Table 1 lists the pellet samples from the comminution on the hammer
and roller mills.

Identifier	DE 1658-4	DE 1663-16	VF 21 4, VF 21 6,	VE 21 8 VE 22 8
			VF 22 4, VF 23 4	VF 21 8, VF 33 8
mill type	Loesche roller mill LM $23.2\mathrm{D}$	Hammer mill	Loesche roller	mill LM 19.2 D
power plant	AVV	HEV	AN	ΛV
sampling method	*r	*f	*r	*r, *vc
mill screen size		$2\mathrm{mm}$		
rotating classifier	1		1	l
energy consumption	$10\mathrm{kWh}\mathrm{t}^{-1}$	$29\mathrm{kWh}~\mathrm{t}^{-1}$	8 kWl	h t $^{-1}$
bulk density of pellets	$1.29{ m g}~{ m cm}^{-3}$	$1.31{\rm g~cm^{-3}}$	-	
moisture	5.2%	7.8%	6.3-6	5.7 %
composition	10% softwood + $90%$ hardwood		50% softwood +	50% hardwood

 Table 1: Sample specification, comminution parameters and composition of milled pellets.

*r - rotorprobe, *f - filtering, *vc - vacuum cleaner

The 8 mm pellets were produced in Latvia (LatGran), and used to 213 make DONG Energy samples (DE 1658-4 and DE 1663-16), as shown in 214 Table 1. The identifiers DE 1658-4 and DE 1663-16 include the company 215 name (DONG Energy) which is followed by the sample number; 4 and 15 216 include the fourth and the sixteenth samples taken, respectively. Pellets con-217 sist of 10% hardwood and 90% softwood, and were produced from 70% fine 218 sawdust and 30% coarse sawdust. A larger percentage of softwood contains 219 Scots pine (Pinus sylvestris), Norway spruce (Picea abies), European aspen 220 (Populus tremula), whereas a smaller percentage of hardwood consists of 221 birch (Betula spp) and alder (Alnus spp), according to the feedstock classi-222 fication described in EN ISO 17225-1:2016. The age of the roundwood with 223 bark used for making pellets ranged from 15 to 95 years. The particle size 224 distribution of the original sawdust prior to pelletization is shown in Table 2: 225

Table 2: Particle size distribution of the raw material used for making DE 1658-4 and DE 1663-16 samples. The particle size was determined by sieving.

mm	%
> 2.8	1.2
2.0-2.8	5.5
1.4-2.0	14.9
1.0-1.4	18.7
0.5-1.0	27.7
0.25-0.5	16.4
< 0.25	15.8

The 4 mm pellets were produced in Estonia (Heatlets), and were used 226 to make the AMV samples (VF 21 4, VF 21 6, VF 22 4, VF 23 4, VF 33 8, 227 VF 21 8), as shown in Table 1. The identifiers 21, 22, 23, and 33 are sample 228 numbers; the numbers 4, 6, and 8 represent the mass flow rate (kg s⁻¹) in 229 the pipelines running from the mill. The numbers 2 and 3 in parentheses 230 found in abbreviations VF (2)3 4 and VF (3)3 8, indicate the second and 231 the third mill of the power plant. The pellets consist of 50% alder (Alnus 232 spp) and 50% softwood (Scots pine 45%, Norway spruce 5%), and were 233 manufactured from 75% fine sawdust and 25% coarse sawdust, according to 234 the feedstock classification described in EN ISO 17225-1:2016. The particle 235 size distribution of the raw feedstock used to make the VF pellets is shown 236 in Table 3: 237

Table 3: Particle size distribution of the raw material (VF 21 8 kg s⁻¹ and VF 33 8 kg s⁻¹) before pelletilization determined by sieving.

mm	%
> 3.15	1.92
2.8-3.15	0.08
2.0-2.8	2.32
1.4-2.0	76.36
0-1.4	19.3

238 5. Results

239 5.1. Comparison of the particle size characterization methods

In this work, both sieving and 2D dynamic imaging were used. Therefore, it is instructive to compare the samples using both methods. Samples (DE 1658-4, DE 1663-16, VF 21 8 kg s⁻¹, and 33 8 kg s⁻¹) of the pulverized biomass were measured using the CAMSIZER and presented as a cumulative distribution, based on volume (Q₃), over the $x_{Ma,min}$ diameter. The 2D dynamic imaging data and the sieving data are compared in Figure 8:



Figure 8: Cumulative particle size distribution Q_3 , based on volume, for DE 1658-4, DE 1663-16, VF 21 8 kg s⁻¹, and VF 33 8 kg s⁻¹ samples milled in the power plant-scale roller- and laboratory-scale hammer mills, and characterized by sieving and 2D dynamic imaging.

Sieving and 2D dynamic imaging produced very similar size distribu-246 tions, as shown in Figure 8. The particle size analysis indicated that samples 247 DE 1658-4 and DE 1663-16 contained a larger fraction of small particles 248 compared to pulverized biomass obtained after milling the AMV pellets. 249 The comparable results obtained using both sizing techniques justify the ap-250 plication of sieving, when large sample quantities are analyzed, whereas 2D 251 dynamic imaging analysis is more applicable when additional information 252 about geometrical parameters (length, width, etc.) and shape is required. 253

²⁵⁴ 5.2. Effect of sampling method on particle size and shape

The effect of sampling method on particle size and shape was inves-255 tigated using samples VF 21 8 kg s⁻¹ and 33 8 kg s⁻¹. The samples were 256 collected using a vacuum cleaner and a rotorprobe mounted on horizontal 257 piping. Collected particles were subsequently characterized by 2D dynamic 258 imaging. Figure 9 shows that the sampling method affects the measured par-259 ticle size distribution for both samples. The samples collected by the vacuum 260 cleaner showed a large fraction of fines, whereas the rotorprobe samples con-261 tained coarser particles. Since the vacuum cleaner has a larger inlet and the 262 operator can easily move a vacuum cleaner hose inside the pipeline, the large 263 particles do not entrain properly. Meanwhile, by placing the probes perpen-264 dicular to the direction of flow, the rotorprobe has a greater cross section to 265 collect pulverized wood particles. Therefore, a more representative sample 266 is expected from the rotorprobe sampling. However, the flow restrictions in 267 the inlets and cyclone, which was originally designed for coal, may have led 268 to the collection of coarser particles. 269



Figure 9: Influence of sampling method on the particle size distribution for VF 21 8 kg s^{-1} and VF 33 8 kg s^{-1} samples. The 2D dynamic imaging is used for particle sizing. 23

²⁷⁰ 5.3. Effect of pelletization and secondary milling on particle size

Disintegration of 8 mm LatGran pellets was carried out in deionized 271 water for 10 min, followed by drying at 40°C for 4 h in an oven desiccator. 272 Figure 10 shows the particle size distribution of sample VF 33 8 kg s⁻¹ before 273 pelletization, disintegrated pellets and samples were collected after under-274 going secondary comminution on the roller mill. It is thereby possible to 275 quantify the effect of pelletization and secondary comminution on particle 276 size. Figure 10 indicates that the particle size distributions of the sawdust 277 and the disintegrated pellets are similar. Thus, the pelletization process does 278 not appear to modify the sizes of the component particles. However, as also 279 shown in Figure 10, the differences between the particle frequency distribu-280 tions of the disintegrated pellets and the pellets comminuted on the roller 281 mill are large. Secondary comminution step results in a further reduction 282 of the original sawdust particle size by more than 40%. In addition, the 283 particle size of pulverized wood can be affected by the sampling method and 284 the disintegration process of pellets. 285

The sphericity (mean SPHT of all samples = 0.56) and the aspect ratio 286 (mean AR of all samples = 0.51) of the comminuted pellets indicate that 287 particles can be considered as cubic, as shown in Figure 10(a). The SEM 288 microscopy shows that the largest particles indeed have a cubic shape (Fig-289 ure 11(c), whereas smaller particles show various shapes with broken edges 290 (Figure 11(d)). The original (before pelletilization) sawdust particles and 291 particles of the disintegrated pellets are elongated (mean SPHT of all samples 292 ≈ 0.51 ; mean AR of all samples ≈ 0.53), as shown in Figures 10(a) and 10(b). 293 This observation was confirmed by 2D dynamic imaging. Light microscopy 294

confirmed that particles from the original sawdust as well as those in the
disintegrated pellets displayed elongated shapes with small aspect ratios, as
shown in Figures 11(a)-11(b).



Figure 10: Particle size distribution q_3 , based on volume, for VF 33 8 kg s⁻¹ and VF 21 8 kg s⁻¹ samples comminuted in the power plant-scale roller mill, original sawdust samples before pelletization and disintegrated pellets; shape factors (sphericity, aspect ratio) determined by 2D dynamic imaging.



11(c): VF 21 8 kg s⁻¹ pellets (0.71-1 mm) 11(d): VF 21 8 kg s⁻¹ pellets (< 0.18 mm)

Figure 11: Light microscopy images of (a) sawdust before pelletization, (b) disintegrated pellets, and SEM images after comminution in the power plant-scale roller mill (VF 21 8 kg s⁻¹) and manually separated in two fractions (c) 0.71-1 mm and (d) < 0.18 mm.

Typically, the sphericity and the aspect ratios of the original sawdust, disintegrated pellets and comminuted pellets increase with particle size, indicating that particles become more spherical and less elongated as their size increases. However, the results from particles > 2 mm were to be considered as non-representative in terms of shape description because the population of this fraction was too small.

³⁰⁴ 5.4. Influence of mill type on particle size and shape

Bond [12] concluded that biomass type has a greater impact on particle shape than mill type. Rose [14] indicated that particle size and shape are mainly affected by mill type. In the present study, wood pellets were comminuted in roller- and hammer mills. Different types of wood pellets were comminuted on a roller mill to investigate the impact of feedstock and operational parameters of the mill on particle size and shape.

In Figure 12, the differences in particle size of pellets comminuted in 311 the roller mill (DE 1658-4, VF 21 8 kg s⁻¹, and VF 33 8 kg s⁻¹) and in the 312 hammer mill (DE 1663-16) are notable. Comminution in the hammer mill 313 produced a larger fraction of fine particles, whereas comminution in the roller 314 mill generated a more homogeneous product containing longer particles. The 315 differences in particle size between samples DE 1658-4, VF 21 8 kg s^{-1} , and 316 VF 33 8 kg s⁻¹, comminuted in the roller mills at AMV and AVV, are also 317 substantial. 318



Figure 12: Particle frequency distribution q_3 , based on volume, for DE 1658-4, DE 1663-16, VF 21 8 kg s⁻¹, and VF 33 8 kg s⁻¹ samples milled in the power plant-scale roller- and laboratory-scale hammer mills, and characterized by 2D dynamic imaging.

The primary cause for the particle size differences among samples milled 319 in the roller mill are: pellet wood composition and differences in the classi-320 fiers of the mills. The comminution in the roller and hammer mills led to 321 similar shaped-particles. The particles were rectangular (SPHT $\approx 0.5-0.7$); 322 the aspect ratios were similar at AR = 0.3. Symmetry and convexity of the 323 particles obtained by milling using either the hammer- or roller mill were also 324 similar. The comminution in both mills did not cause particle breakage, and 325 led to symmetrical polygonal particles containing holes (Symm = 0.7-0.9; 326 Conv ≈ 0.95), as shown in Figures 13(c)-13(d). Also the SEM microscopy 327 indicates that the differences in particle shape were small, as shown in Fig-328



³²⁹ ure 14. Thus, the particles had similar shapes independent of mill type and³³⁰ particle size.

Figure 13: Shape factors (sphericity, aspect ratio b/l, symmetry and convexity) and size frequency distribution q_3 , based on volume, for DE 1658-4, DE 1663-16, VF 21 8 kg s^{-1} , and VF 33 8 kg s^{-1} samples comminuted in the power plant-scale rollerand laboratory-scale hammer mills, and characterized by 2D dynamic imaging.



14(a): Pellets DE 1658-4 (roller mill, 0.71-14(b): Pellets DE 1658-4 (roller mill, $<1\,{\rm mm})$ 0.18 mm)



14(c): Pellets DE 1663-16 (hammer mill, 14(d): Pellets DE 1663-16 (hammer mill, $< 0.71\text{-}1\,\mathrm{mm})$ $0.18\,\mathrm{mm})$

Figure 14: SEM images of particles from pellets comminuted on power plant-scale roller and laboratory-scale hammer mills, and manually separated in particle size fractions < 0.18 mm and 0.71-1 mm.

331 5.5. Influence of mass flow rate on particle size and shape

The impact of fuel mass flow rates in the pipelines, which supply the 332 wood dust to the burners, was studied by examining powder flow rates of 333 4, 6, and 8 kg s^{-1} . The milled wood was delivered to the burner using four 334 different pipes, but the particle size of the wood dust among the three output 335 pipes was measured. It was reckoned that at a flow rate of 8 kg s^{-1} , particle 336 fragmentation in the pipeline may occur. However, Figure 15(a) shows that 337 increasing biomass flow rate from 4 to 8 kg s^{-1} did not significantly affect 338 particle size. Differences in the milled wood particle size in the four pipes were 339 expected to occur due to variations in throughput of the rotational classifier 340 and due to different pressure drops caused by the pipe bends and length. In 341 Figure 15(b), the particle size distributions of the wood transported at 4 kg 342 s^{-1} show that particle size was similar among the three output pipes. 343



15(b): Burner pipes impact

Figure 15: Particle size distribution of pellets milled in the power plant-scale roller mill (20) (a) different feedstock flow rates and (b) in different pipelines (21, 22, 23). The particles were sampled using the rotorprobe.

³⁴⁴ 5.6. Impact of roller mill size on particle size and shape

A kilogram of VF 21 8 kg s⁻¹ pellets was put into the funnel of the labo-345 ratory mill, as shown in Figure 6, which was operated at 15° roller inclination 346 and 10 rpm. Figure 16 shows the particle size distribution after milling sam-347 ple VF 21 8 kg s⁻¹ in the laboratory-scale mill and in the power plant-scale 348 Loesche roller mill at AMV. It can be observed that the laboratory-scale 349 mill at TU Clausthal provides comparable results to those obtained using 350 the power plant-scale roller mill, currently operated by AMV, with respect 351 to particle size distribution and particle shape. According to the conducted 352 analysis, the results from the laboratory-scale roller mill well represented the 353 changes in particle size and shape imposed by comminution in the power 354 plant mill. 355



Figure 16: Particle frequency distribution q_3 , based on volume, for VF 21 8 kg s⁻¹ sample comminuted in the laboratory-scale and power plant-scale roller mills, and characterized by 2D dynamic imaging.



Figure 17: Shape factors (sphericity, aspect ratio b/l, symmetry and convexity) and size frequency distribution q_3 , based on volume, for VF 21 8 kg s⁻¹ sample comminuted in the laboratory-scale roller mill and the power plant-scale mill, and characterized by 2D dynamic imaging.

356 6. Discussion

The investigations showed only a small difference (less than 5%) in a particle size of the original wood powder (used to produce the pellets) and the powder obtained after disintegrating of the pellets. The results obtained from material derived from the power plant-scale roller mills clearly demonstrated that most pellets were broken down to sizes from 0.75 to 0.1 mm which are substantially smaller than sizes of original powder (sawdust) after milling.

The impact of different mill types on both particle size and shape was 363 studied using the roller- and hammer mills. The results showed that mill type 364 has the most significant influence on the size distribution of the pulverized 365 wood. The analyzed hammer-milled samples contained a large fraction of fine 366 particles compared to the roller-milled samples. The particle size was affected 367 by sampling methods; the vacuum cleaner sampling was biased towards small 368 particles. Further studies are required to determine the effect of sampling 369 method on pulverized wood particle size and shape. The pellet samples 370 from DONG Energy which contained a large percentage of softwood (90%)371 produced finer particles after milling than the AMV pellets which were made 372 out of a mixture of 50% softwood and 50% hardwood. 373

The shape of milled wood was only slightly influenced by the mill type. The results showed a small variation in sphericity, aspect ratio and convexity. The sphericity and aspect ratio for particle fractions of size < 2 mm remained unaltered. For larger particles, the shape characterization does not provide statistically significant results due to small sample amounts. It was observed that longer particles were rectangular in shape and had more broken edges than their smaller counterparts.

The hammer and the roller mills require different energy inputs for conducting comminution. The input energy of the hammer mill was 29 kWh t^{-1} whereas the roller mills required up to 10 kWh t^{-1} under full load. Thus, the roller mills are more energy efficient, confirming the results of Tamura et al. [27].

Pellets comminuted in a power plant roller mill were compared with the 386 pellets comminuted in the laboratory-scale roller mill at TU Clausthal. The 387 particle size and shape of milled wood, after milling the pellets either in the 388 laboratory-scale or in the power plant Loesche roller mill, were similar. Thus, 389 the results from the laboratory-scale mill represented well by the pilot plant 390 size roller mill. This comparison was made for one sample only. Further 391 systematic studies are needed to establish a confident relationship between 392 the laboratory-scale and power plant-scale milling processes. 393

³⁹⁴ 7. Conclusion

An experimental study was carried out to investigate the milling characteristics of biomass pellets milled in Danish power plants. Several samples, comminuted in hammer- and roller mills, were analyzed to establish a relationship between mill type, pellet wood composition (softwood/hardwood) and the size and shape of milled wood. The particle size and shape characterization was conducted using sieving and 2D dynamic imaging.

The mill type and pellet wood composition strongly affected particle size 401 and to a lesser degree particle shape. The secondary comminution of pellets 402 in the hammer and roller mills produced milled wood that contained particles 403 from 0.75 to 0.1 mm which are substantially smaller than the original sawdust 404 particles used in pelletizing. The secondary comminution in the power plant 405 mills produced rectangular particles. No variations in particle size with the 406 milled wood flow rate were observed. No fragmentation of particles in the 407 pipelines, which transport the milled wood to the burners, occurred. 408

409

Hammer mills were shown to require more energy than roller mills. The

 $_{410}$ comminution in the roller mill generated more coarse particles (> 0.5 mm) $_{411}$ than milling in the hammer mill.

The pellets comminution, in the Loesche power plant-scale roller mill and in the laboratory-scale roller mill, resulted in very similar particle size distributions.

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