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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)
AR	Aspect ratio
A_{convex}	Particle convex area (m^2)
A_{real}	Particle projection area (m^2)
b	Particle width (m)
$Conv$	Convexity
d	Diameter (m)
l	Particle length (m)
m	Number of size classes
P	Perimeter of a particle projection (m)
$\overline{q_3}$	Histogram (% mm^{-1})
Q_3	Cumulative particle distribution, based on volume (% mm^{-1})
q_3	Frequency particle distribution, based on volume (% mm^{-1})
r_1, r_2	Distances from the area center to the particle edges (m)
$SPHT$	Circularity (Sphericity)
$Symm$	Symmetry
V	Volume (m^3)
$x_{Fe,max}$	Feret maximum diameter (m)
$x_{Ma,min}$	Martin minimum diameter (m)

Subscripts

i	Number of the size class with upper limit 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 CO_2 emissions can be decreased by the substitution of biomass in pulverized combustion due to the lower regeneration time of biomass compared to bituminous coal. Thus, CO_2 released using biofuels will be reconsumed faster by other plants via photosynthesis than the time needed to regenerate coal. The milling process is a necessary step in suspension fuel firing [1]. Size reduction improves conversion processes due to the creation of larger reactive surface areas [2, 3]. Biomass is due to its fibrous structure difficult to mill. An increased energy input into biomass comminution affects the total efficiency of power plants, and often causes problems with flame stability and burnout when large particles remain after milling.

The common method for preparing biomass for suspension firing is to pelletize lignocellulosic materials, and then pulverize the biomass pellets using coal roller mills [4]. A number of studies [3, 5–10] have investigated the influence of mill type on both the particle size and shape. Momeni [5] showed that comminuting woody pellets in hammer and roller mills produced significantly different sized particles. In other investigations [6, 8], higher fractions of fine particles were obtained after comminution in a hammer mill compared to milling using a knife mill. In agreement with this observation, the energy consumption of the knife mill was found in all cases to be smaller than that of the hammer mill [7, 8]. The feedstock type (hardwood, straw, corn cobs and corn stover) affected the energy consumption of the hammer and disk mills [9]. The energy consumption for the comminution of dry pellets was lower for the hammer mill than for the disk mill, and the particle size distribution was broader with larger particle aspect ratios after comminution in the hammer mill [10]. In addition, it was reported that a high moisture content ($> 20\,\%$) increased the specific energy consumption by $50\,\%$ [10]. It appeared that different feedstocks (switchgrass, corn and soybean) showed differences in the particle size and shape during comminution and generated particles with various morphological properties [11]. Previous investigations of biomass comminution demonstrate disagreements in terms of the effect that mill and feedstock type have on particle shape. Bond [12] and Heywood [13] reported that fuel type has a stronger influence on the particle shape than mill type, whereas Rose [14] showed that mill type mainly affects particle shape. Generally, little is known about the effect of mill type on particle shape and size when lignocellulosic materials are milled.

In this study, the impacts of mill and feedstock type on particle size and shape were investigated. Wood pellets are comminuted using a laboratory-scale 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.

2. Materials and methods

Raw pellets, without additives or binding agents, were provided by the companies LatGran (Latvia) and Heatlets (Estonia). The pellets were produced in the process shown in Figure 1. Wood logs with diameters of 5-60 cm and length of 3-4 m were initially dried, and then shredded in a mobile shredder to 8-45 mm. The primary comminution includes the milling of wood chips to the particle size of 0.5-2 mm in diameter and 1 cm in length by a knife ring flaker and a drop feed chipper, and sawdust milling in a hammer mill to obtain a homogeneous and fine material below 1.5 mm in size. The sawdust before being pelletized, contained 75 % particles following the process described in Figure 1 and contained 25 % coarse bark sawdust residues from 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.

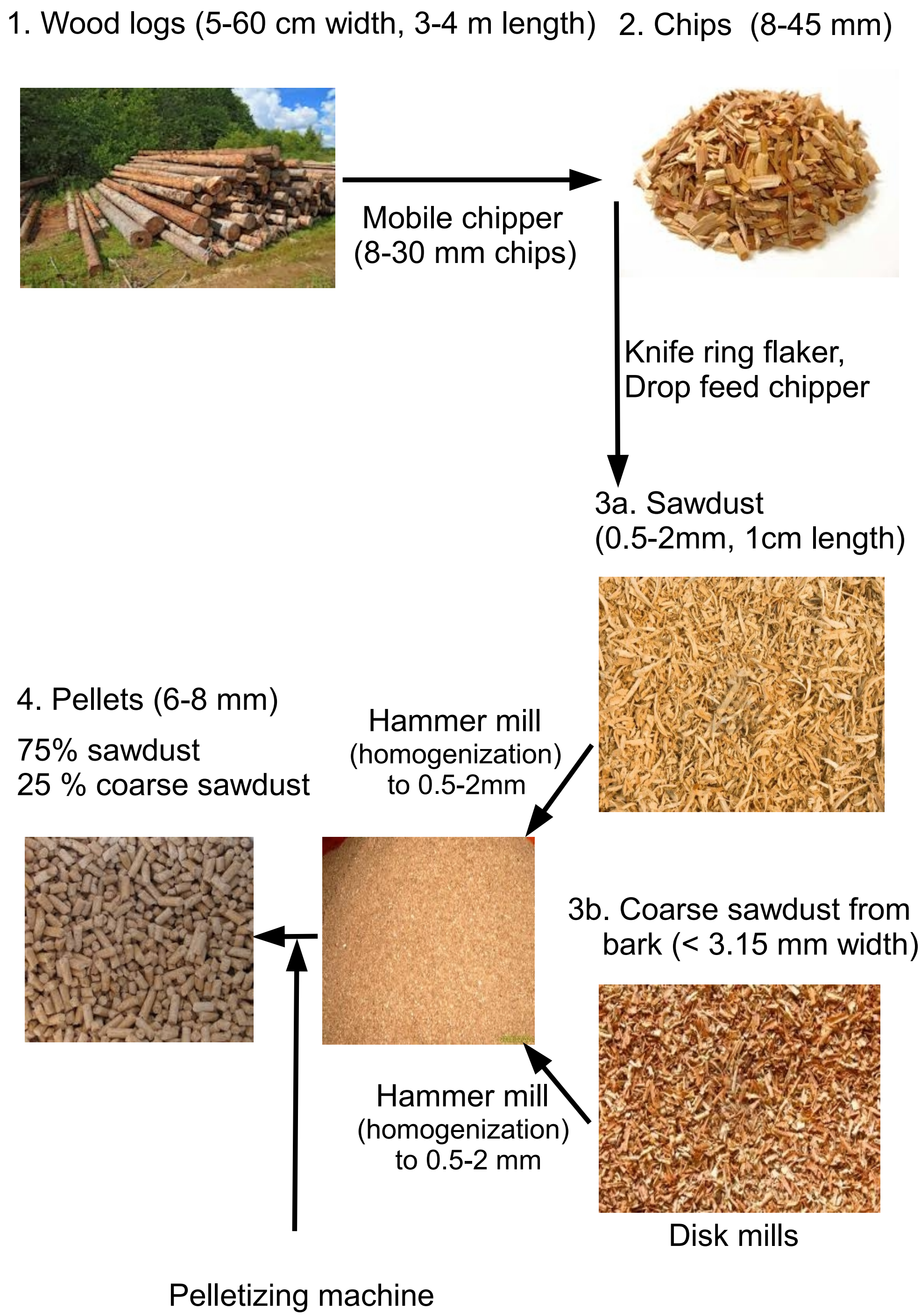


Figure 1: Wood pellets production from (1) Wood logs to (2) Chips, (3a) Sawdust combined with (3b) Coarse sawdust from bark and to (4) Pellets.

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

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

PT100 (Retsch Technology, Germany).

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

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

The Martin minimal ($x_{Ma,min}$) and Feret maximal ($x_{Fe,max}$) 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 ($x_{Ma,min}$) 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

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

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

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

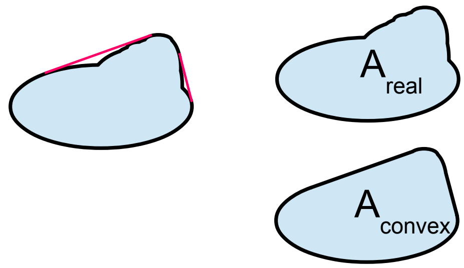


Figure 2: Definition of convexity.

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

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

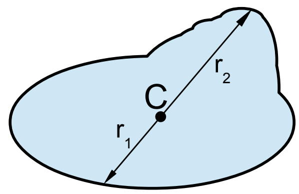


Figure 3: Definition of symmetry.

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

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

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 (q_3), 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 were defined based on three sizes within the entire population: d10, d50, d90. The d50 value is the median particle size within the population, with 50 % of the population greater than this size, and 50 % smaller than this size. Similarly, 10 % of the population is smaller than the d10 size; while 90 % of the population is smaller than the d90 size [20]. All measurements were conducted in triplicate to establish repeatability which was better than 95 %, as shown in the supplemental material. The measurement inaccuracy in sieving analysis was mainly caused by weighing errors.

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 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.

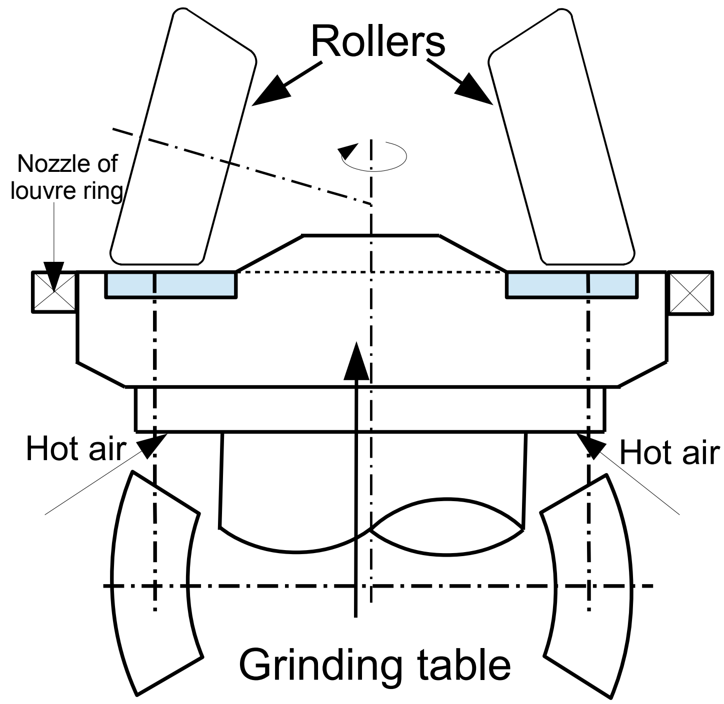


Figure 4: A schematic representation of a power plant-scale roller mill [21–23].

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 $70\,\mathrm{t\,h^{-1}}$.

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.

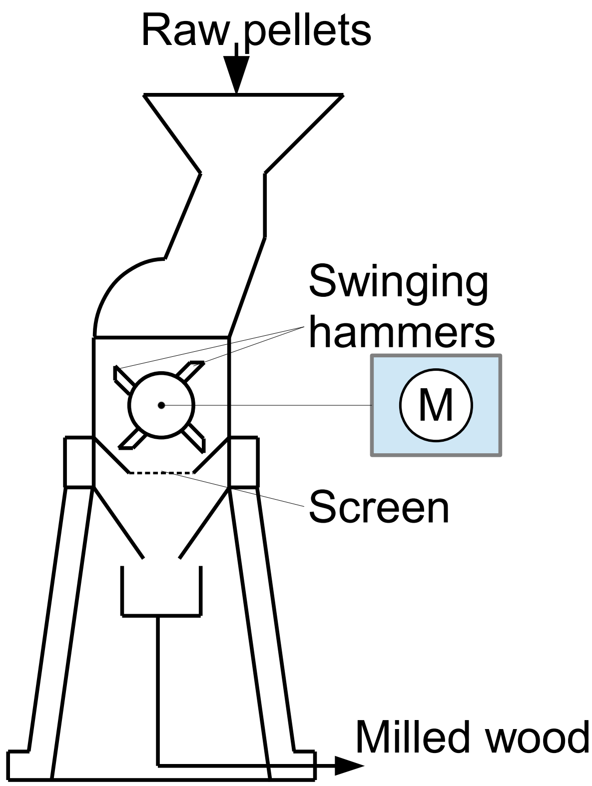


Figure 5: A schematic representation of a hammer mill [24].

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:

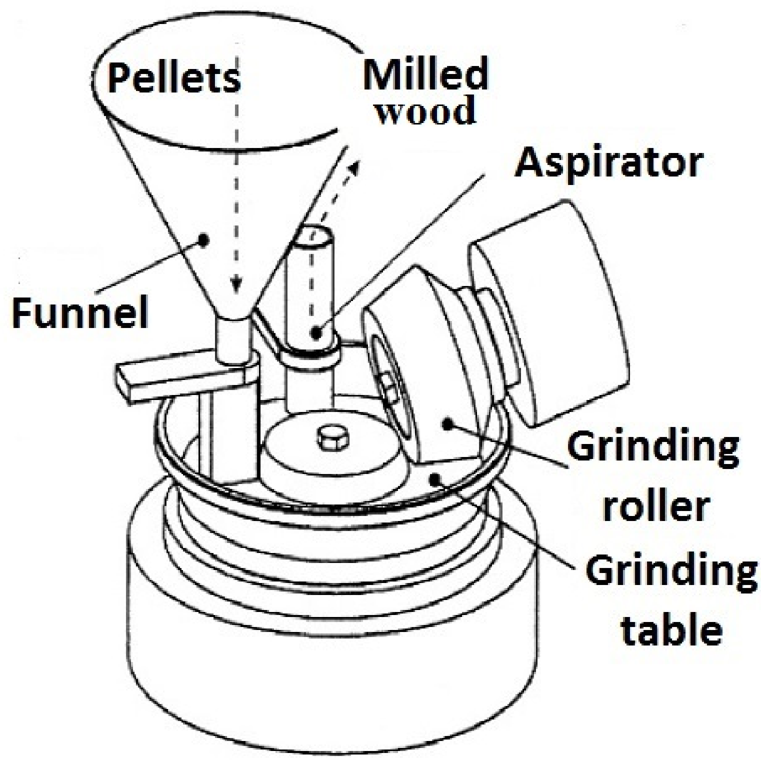


Figure 6: A schematic representation of a laboratory-scale roller mill at TU Clausthal [26].

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 lignocellulosic materials. The mill is equipped with transducers for adjusting the torque, the grinding force and the gap between the roller and the table bottom [26]. The table diameter is 150 mm and the width is 42 mm, the middle roller diameter is 100 mm with a roller width of 40 mm. The maximal roller inclination is 15 °, the maximal motor power is 5.5 kW, and table revolutions vary from 5 to 150 min^{-1}. Throughput of the laboratory-scale roller mill is between 11 and 14.7 kg h^{-1}.

Rotorprobe sampling method. The material, comminuted in both the laboratory- and 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.

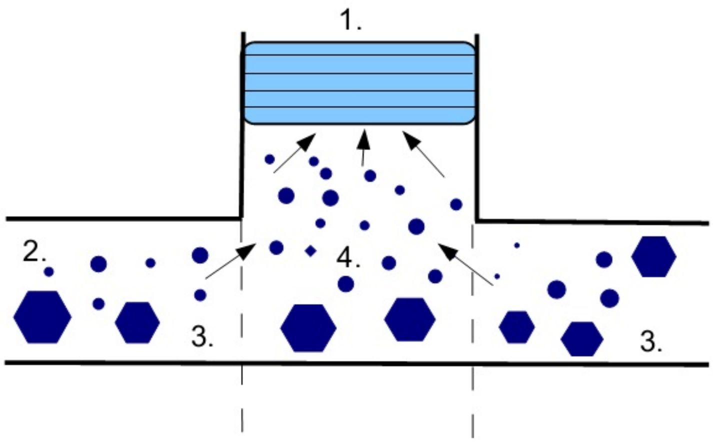


Figure 7: Vacuum cleaner sampling method: (1) vacuum cleaner, (2) particles flow in the pipe, (3) sector of flow before and after sampling and (4) sampling sector.

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.

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

Identifier	DE 1658-4	DE 1663-16	VF 21 4, VF 21 6, VF 22 4, VF 23 4	VF 21 8, VF 33 8
mill type	Loesche roller mill LM 23.2 D	Hammer mill	Loesche roller mill LM 19.2 D	
power plant	AVV	HEV	AMV	
sampling method	*r	*f	*r	*r, *vc
mill screen size		2 mm		
rotating classifier	1		1	
energy consumption	10 kWh t^{-1}	29 kWh t^{-1}	8 kWh t^{-1}	
bulk density of pellets	1.29 g cm^{-3}	1.31 g cm^{-3}	-	
moisture	5.2 %	7.8 %	6.3-6.7 %	
composition	10 % softwood + 90 % hardwood		50 % softwood + 50 % hardwood	

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

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

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

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

5. Results

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 (Q_3), over the $x_{Ma,min}$ diameter. The 2D dynamic imaging data and the sieving data are compared in Figure 8:

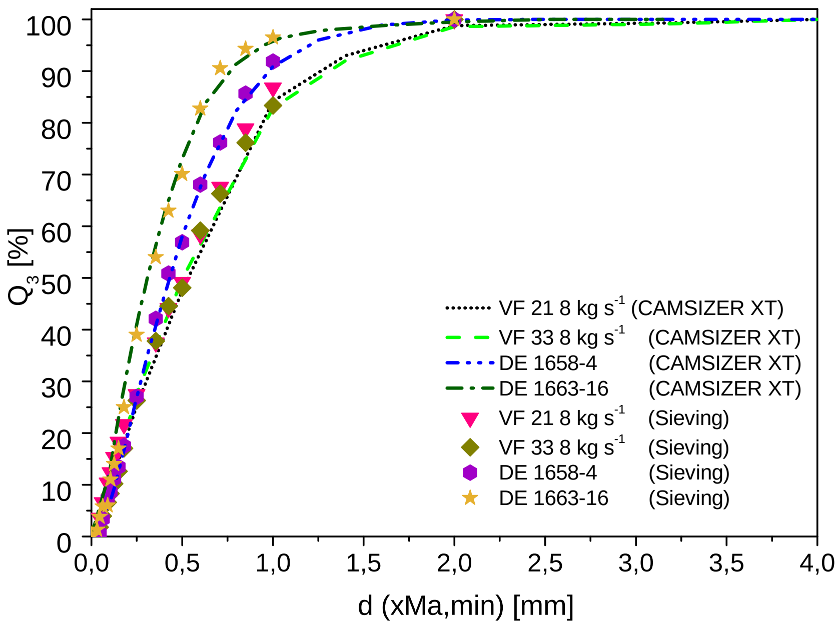
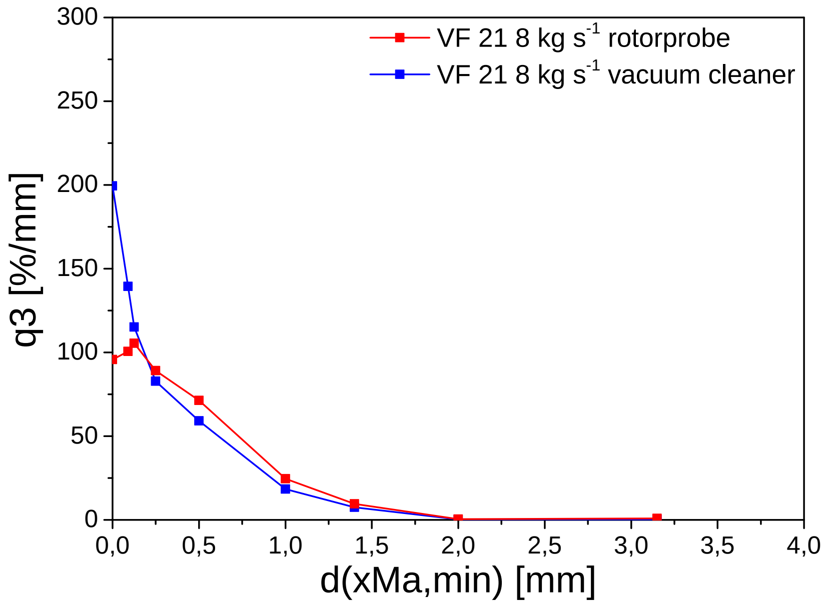


Figure 8: Cumulative particle size distribution Q_3, based on volume, for DE 1658-4, DE 1663-16, VF 21 8 kg s^{-1}, and VF 33 8 kg s^{-1} samples milled in the power plant-scale roller- and laboratory-scale hammer mills, and characterized by sieving and 2D dynamic imaging.

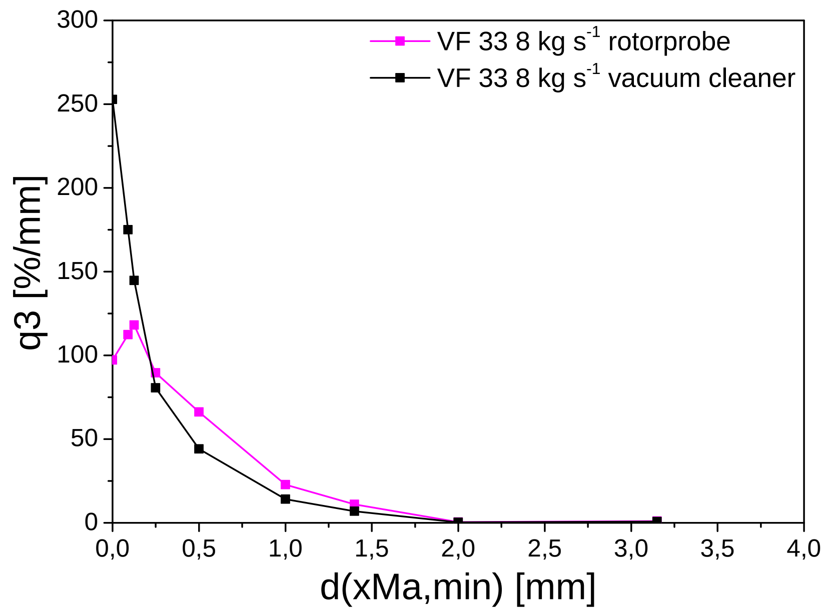
Sieving and 2D dynamic imaging produced very similar size distributions, as shown in Figure 8. The particle size analysis indicated that samples DE 1658-4 and DE 1663-16 contained a larger fraction of small particles compared to pulverized biomass obtained after milling the AMV pellets. The comparable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

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

The effect of sampling method on particle size and shape was investigated using samples VF 21 8 kg s^{-1} and 33 8 kg s^{-1}. The samples were collected using a vacuum cleaner and a rotorprobe mounted on horizontal piping. Collected particles were subsequently characterized by 2D dynamic imaging. Figure 9 shows that the sampling method affects the measured particle size distribution for both samples. The samples collected by the vacuum cleaner showed a large fraction of fines, whereas the rotorprobe samples contained coarser particles. Since the vacuum cleaner has a larger inlet and the operator can easily move a vacuum cleaner hose inside the pipeline, the large particles do not entrain properly. Meanwhile, by placing the probes perpendicular to the direction of flow, the rotorprobe has a greater cross section to collect pulverized wood particles. Therefore, a more representative sample is expected from the rotorprobe sampling. However, the flow restrictions in the inlets and cyclone, which was originally designed for coal, may have led to the collection of coarser particles.



9(a): Sample VF 21 8 kg s^{-1}



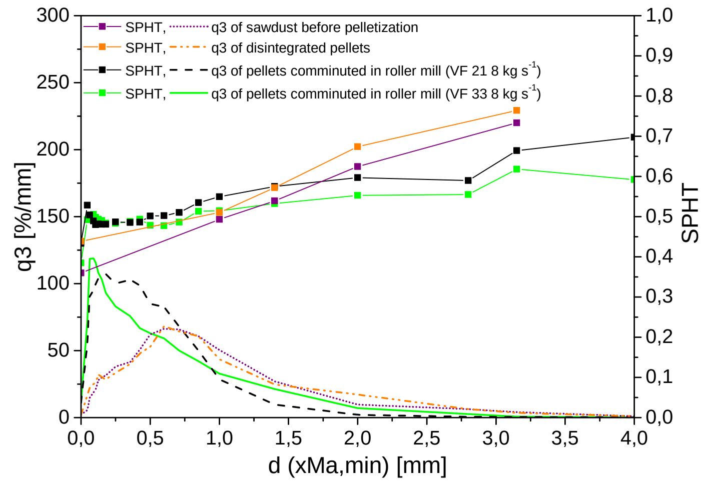
9(b): Sample VF 33 8 kg s^{-1}

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.

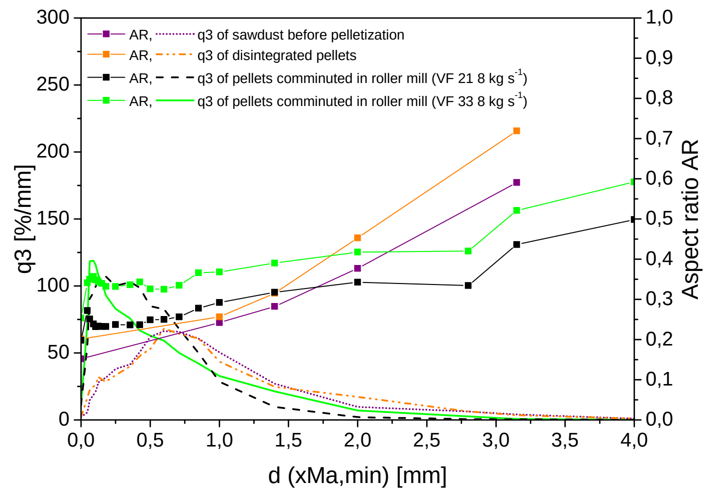
5.3. Effect of pelletization and secondary milling on particle size

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

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



10(a): Sphericity

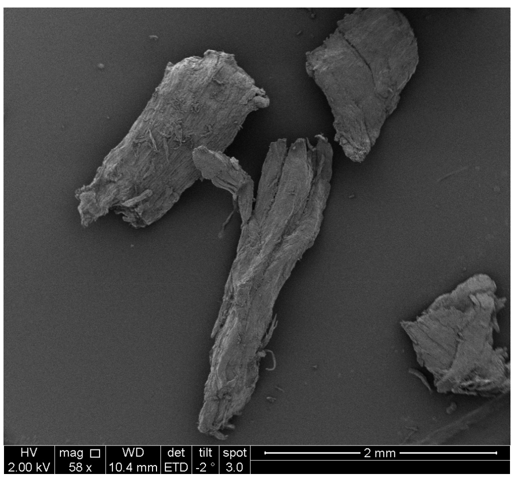


10(b): Aspect ratio

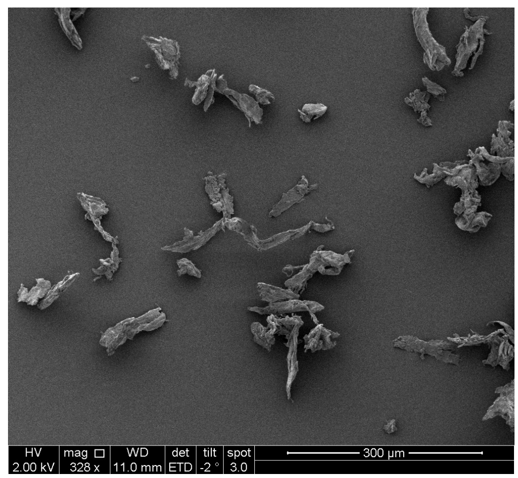
Figure 10: Particle size distribution q_3, based on volume, for VF 33 $8\,\mathrm{kg\ s^{-1}}$ and VF 21 $8\,\mathrm{kg\ s^{-1}}$ samples comminuted in the power plant-scale roller mill, original sawdust samples before pelletization and disintegrated pellets; shape factors (sphericity, aspect ratio)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

11(a): Sawdust particles before pelletization

11(b): Particles from disintegrated pellets



11(c): VF 21 $8\,\mathrm{kg\,s^{-1}}$ pellets (0.71-1 mm)



11(d): VF 21 $8\,\mathrm{kg\,s^{-1}}$ 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 $8\,\mathrm{kg\,s^{-1}}$) 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 $> 2\,\mathrm{mm}$ were to be considered as non-representative in terms of shape description because the population of this fraction was too small.

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 the roller mill (DE 1658-4, VF 21 $8\,\mathrm{kg\ s^{-1}}$, and VF 33 $8\,\mathrm{kg\ s^{-1}}$) and in the hammer mill (DE 1663-16) are notable. Comminution in the hammer mill produced a larger fraction of fine particles, whereas comminution in the roller mill generated a more homogeneous product containing longer particles. The differences in particle size between samples DE 1658-4, VF 21 $8\,\mathrm{kg\ s^{-1}}$, and VF 33 $8\,\mathrm{kg\ s^{-1}}$, comminuted in the roller mills at AMV and AVV, are also substantial.

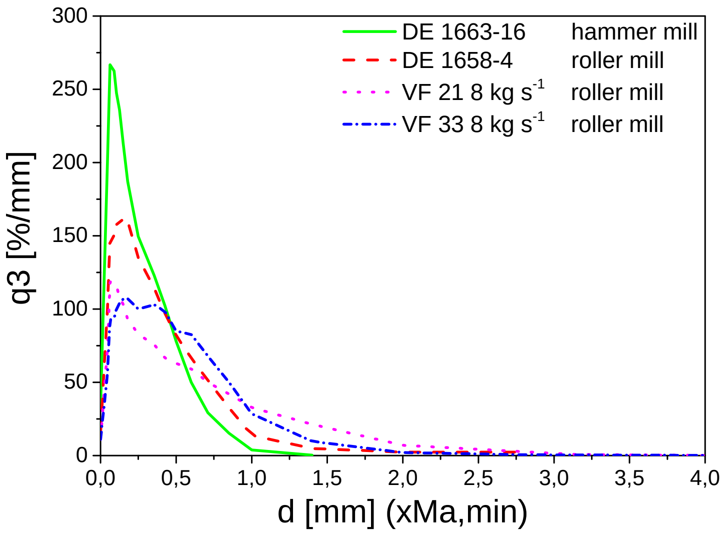
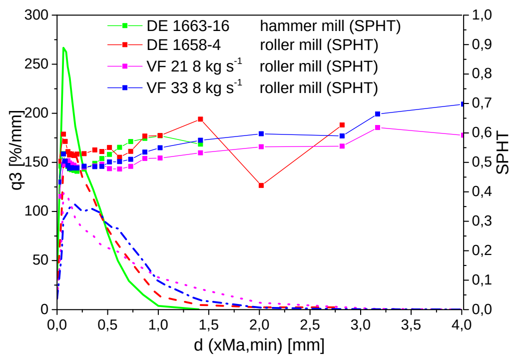
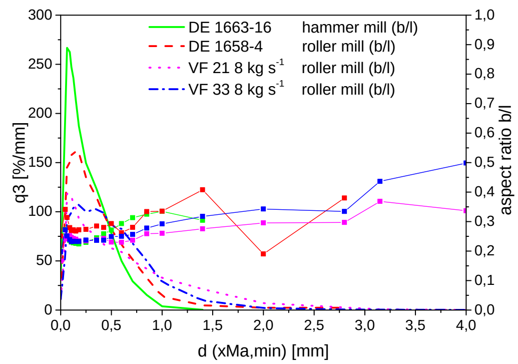


Figure 12: Particle frequency distribution q_3, based on volume, for DE 1658-4, DE 1663-16, VF 21 $8\,\mathrm{kg\ s^{-1}}$, and VF 33 $8\,\mathrm{kg\ s^{-1}}$ samples milled in the power plant-scale roller- and laboratory-scale hammer mills, and characterized by 2D dynamic imaging.

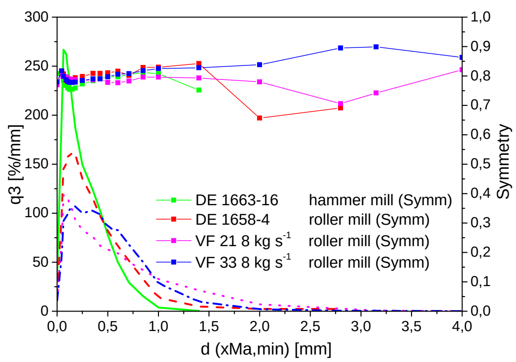
The primary cause for the particle size differences among samples milled in the roller mill are: pellet wood composition and differences in the classifiers of the mills. The comminution in the roller and hammer mills led to similar shaped-particles. The particles were rectangular (SPHT $\approx$ 0.5-0.7); the aspect ratios were similar at AR = 0.3. Symmetry and convexity of the particles obtained by milling using either the hammer- or roller mill were also similar. The comminution in both mills did not cause particle breakage, and led to symmetrical polygonal particles containing holes (Symm = 0.7-0.9; Conv $\approx$ 0.95), as shown in Figures 13(c)-13(d). Also the SEM microscopy indicates that the differences in particle shape were small, as shown in Figure 14. Thus, the particles had similar shapes independent of mill type and particle size.



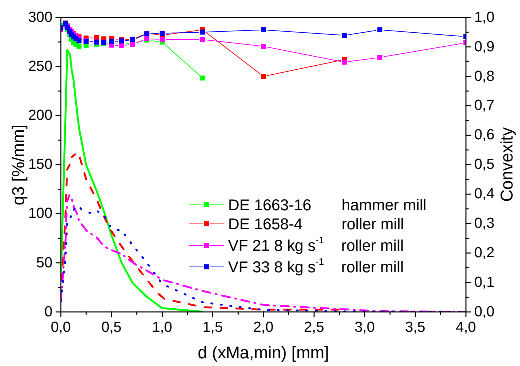
13(a): Sphericity (SPHT)



13(b): Aspect ratio b/l

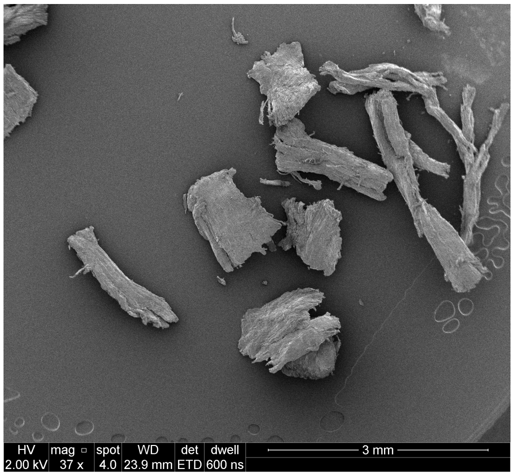


13(c): Symmetry

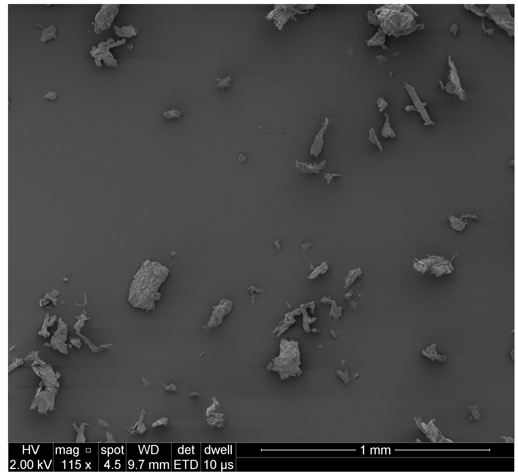


13(d): Convexity

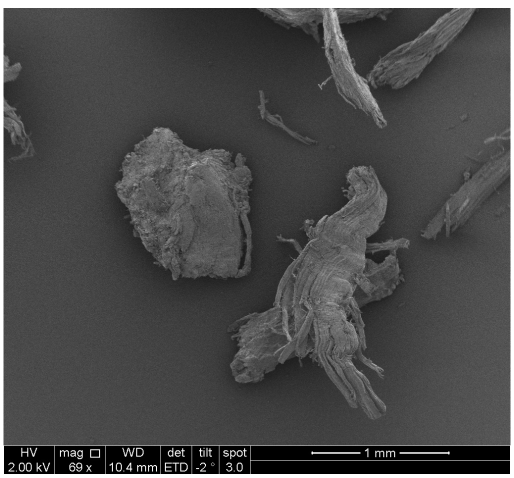
Figure 13: Shape factors (sphericity, aspect ratio b/l, symmetry and convexity) and size frequency distribution q_3, based on volume, for DE 1658-4, DE 1663-16, VF 21 8 kg s^{-1}, and VF 33 8 kg s^{-1} samples comminuted in the power plant-scale roller- and laboratory-scale hammer mills, and characterized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



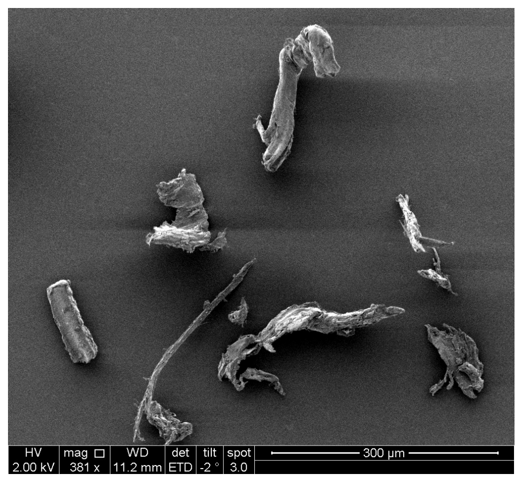
14(a): Pellets DE 1658-4 (roller mill, 0.71-1 mm)



14(b): Pellets DE 1658-4 (roller mill, < 0.18 mm)



14(c): Pellets DE 1663-16 (hammer mill, 0.71-1 mm)

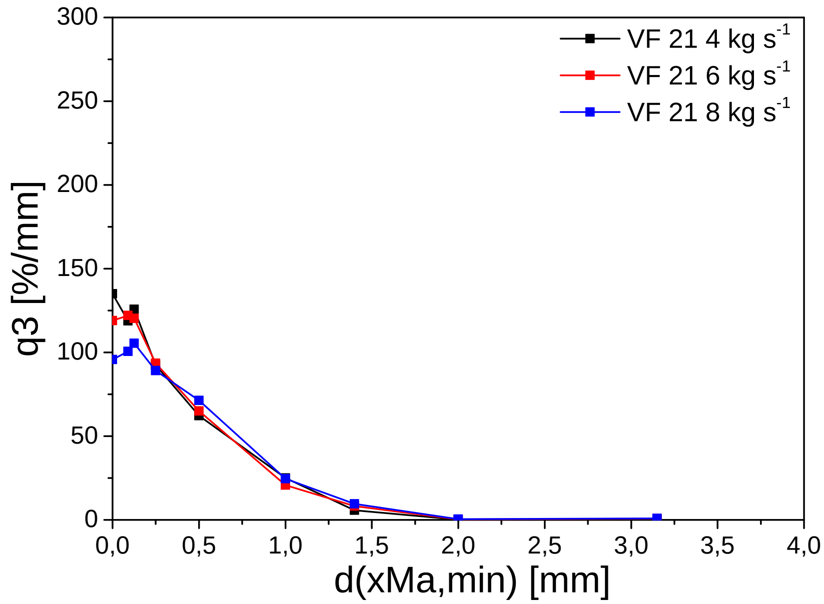


14(d): Pellets DE 1663-16 (hammer mill, < 0.18 mm)

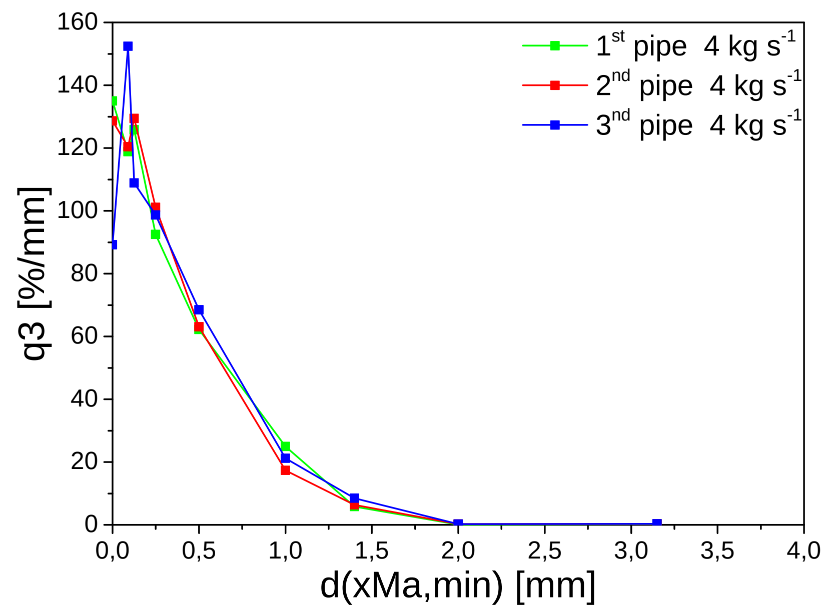
Figure 14: SEM images of particles from pellets comminuted on power plant-scale roller and laboratory-scale hammer mills, and manually separated in particle size fractions < 0.18 mm and 0.71-1 mm.

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



15(a): Mass flow rate impact



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.

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 laboratory mill, as shown in Figure 6, which was operated at 15° roller inclination and 10 rpm. Figure 16 shows the particle size distribution after milling sample VF 21 8 kg s^{-1} in the laboratory-scale mill and in the power plant-scale Loesche roller mill at AMV. It can be observed that the laboratory-scale mill at TU Clausthal provides comparable results to those obtained using the power plant-scale roller mill, currently operated by AMV, with respect to particle size distribution and particle shape. According to the conducted analysis, the results from the laboratory-scale roller mill well represented the changes in particle size and shape imposed by comminution in the power plant mill.

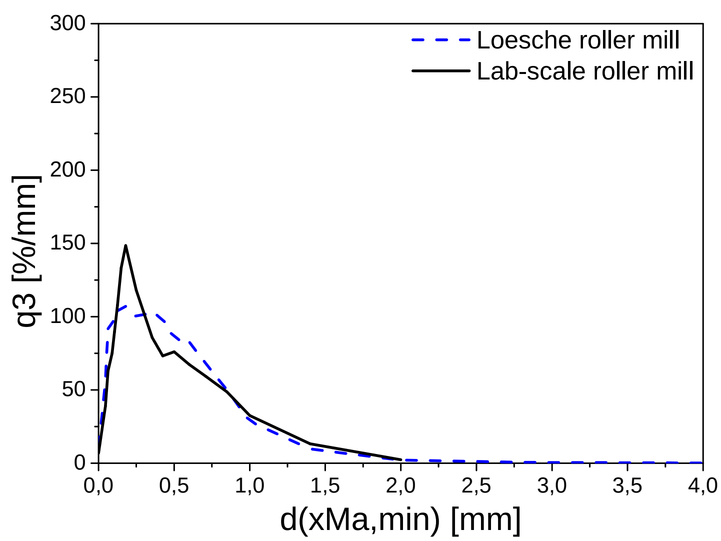
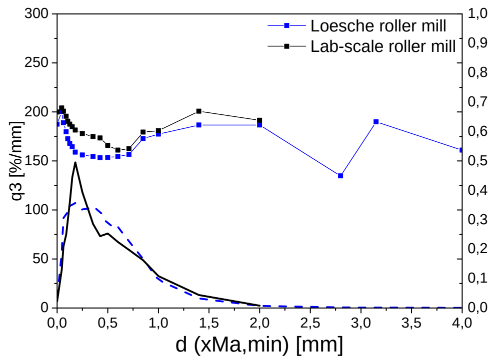
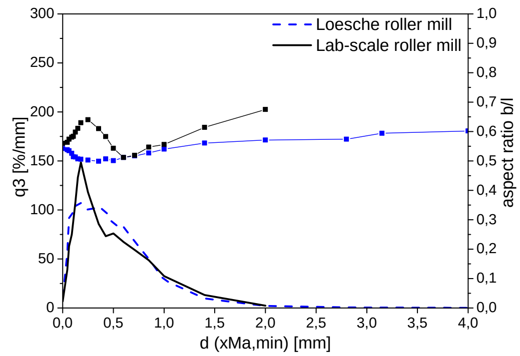


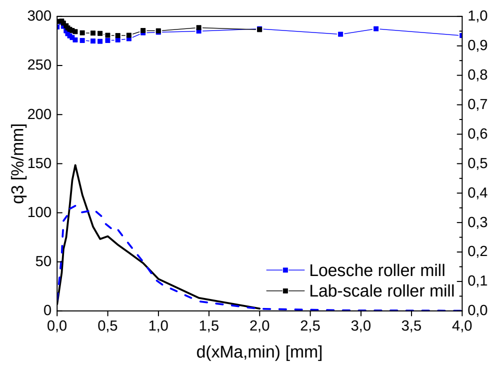
Figure 16: Particle frequency distribution q_3, based on volume, for VF 21 8 kg s^{-1} sample comminuted in the laboratory-scale and power plant-scale roller mills, and characterized by 2D dynamic imaging.



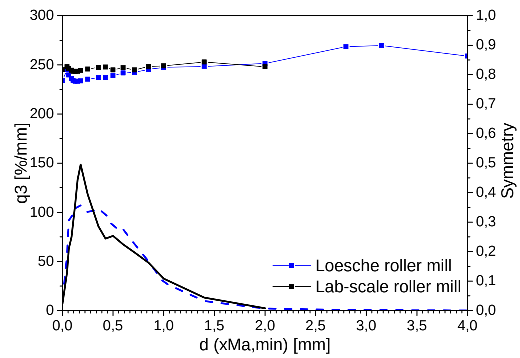
17(a): Sphericity



17(b): Aspect ratio



17(c): Convexity



17(d): Symmetry

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.

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

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

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 and to a lesser degree particle shape. The secondary comminution of pellets in the hammer and roller mills produced milled wood that contained particles from 0.75 to 0.1 mm which are substantially smaller than the original sawdust particles used in pelletizing. The secondary comminution in the power plant mills produced rectangular particles. No variations in particle size with the milled wood flow rate were observed. No fragmentation of particles in the pipelines, which transport the milled wood to the burners, occurred.

Hammer mills were shown to require more energy than roller mills. The comminution in the roller mill generated more coarse particles ($> 0.5\,\text{mm}$) 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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