

Using of high-speed mills for biomass disintegration

G. Karráa¹, T. Ivanova^{1,*}, M. Kolarikova¹, P. Hutla² and V. Krepl¹

¹Czech University of Life Sciences Prague, Faculty of Tropical AgriSciences, Department of Sustainable Technologies, Kamýcká 129, CZ165 21 Prague 6, Czech Republic

²Research Institute of Agricultural Engineering, p.r.i., Drnovská 509, CZ161 01 Prague 6, Czech Republic

*Correspondence: ivanova@ftz.czu.cz

Abstract. The need for mechanical disintegration of biomass is very current topic with regard to the requirements of an agrarian sector, beside the importance of a material's moisture content reduction to be used in further applications. The drawbacks of commonly applied devices are the limited use of moist biomass and high energy consumption for disintegration. In collaboration with LAVARIS company, there were tested two high-speed mills LAV 400/1R with single rotor (used for a first milling) and LAV 300/2R with double rotors (used for a second milling), which were primarily designed for crushing of concrete, rubber and construction waste. The goal of the new technical solution was a disintegration of biomass on example of pine sawdust and miscanthus together with examination of simultaneous drying in order to achieve a desired fraction (particle size) and moisture content of biomass material. Experimental tests on high-speed mills have shown the following results: in case of pine sawdust about 98% of output particle size after passing through the first and second milling was smaller than 1.5 mm, and smaller than 1 mm for miscanthus (sieve analysis method was used for determination), i.e. significant reduction was achieved comparing to initial particle size. Moisture content of the materials after disintegration (first and second) decreased from 37.08% to 8.55% for pine sawdust and from 24.43% to 7.19% for miscanthus. Based on the results, it can be concluded that the mechanical disintegration of biomass by high-speed mills has a great potential to become an effective part of raw materials' pre-treatment technology, not only in agriculture, but also in production of different types of biofuels.

Key words: pine sawdust, miscanthus, particle size, sieve analyses, moisture content.

INTRODUCTION

Size reduction of agricultural products and by-products is a key issue for the further utilization of the materials (Chitoiu et al., 2016) together with a moisture content. Particle size is an important parameter having an impact on the characteristics of loose particulate biomass (e.g. flow ability, compaction, compressibility) as well as mechanical properties of densified biofuels (bulk density, strength, mechanical durability), thus largely affecting their quality and performance (Pietsch, 2008; Tumuluru et al., 2011; Guo et al., 2012; Chaloupková et al, 2016; Muntean et al., 2017; Chaloupková et al., 2018). Mechanical disintegration significantly decreases the size of

materials' particles and biomass volume resulting in the lower costs for storage, transport and use (Guo et al., 2016; Muntean, 2017). Grinding, cutting or crushing is carried out by different types of mills, using various energy sources, where the most widely used is a hammer mill (Chitoiu et al., 2016). For the purpose of biomass disintegration for biofuel production, the devices that operate on the principle of shear action (colloid mills, extruders) or shear forces (blade, striking mills) are commonly applied to disintegrated the materials with a moisture content over 20 wt% (Kratky & Jirout, 2015). However, their disadvantages are in the limited use of moist biomass and high energy demands (Tumuluru, 2018). According to Manlu et al. (2003) besides the grinding degree being a very important indicator, the size reduction has a direct relationship to the energy consumption per unit. Drying of biomass is another crucial operation from technological point of view, where the speed of drying is also affected by size, shape and type of the used material. Thanks to drying the material which would destruct in its natural state very quickly can be stored for a long time, however, drying often involves high energy consumption as well, and that is why it is essential to find/select an optimal drying equipment (Ivanova et al., 2012).

Generally, the importance of developing the sustainable and renewable energy sources, mainly improving the efficiency of such systems for a proper energy saving, is rapidly expanding (Shih et al., 2016). For example, thermo-chemical treatment like combustion or gasification is already known way of biomass utilization for heat and power generation (Kirsanovs et al., 2014), and since the last years a pyrolysis technology attracts an increasing scientific attention, too. However, the process of pyrolysis is energy-intensive (especially rapid pyrolysis), mainly the pre-treatment of a material before the process like pre-drying of biomass (Rogers & Brammer, 2012) as well as size reduction (Choi et al., 2012). Therefore, it is advisable to include disintegration, press or drying unit prior to the pyrolysis reactor (De Jong & Van Ommen, 2014).

High-speed grinding is one of the most efficient and promising solutions for modifying materials in which a large amount of energy is mechanically transferred to the mass of a treated material, thereby changing its reactivity and subsequent properties in addition to the reduction of a material size (Kratky & Jirout, 2015). High-speed grinding performs effective and continuous processing of a very wide range of materials. The treatment of materials by means of high-speed grinding allows to combine the milling effect (surface refinement) with a pronounced mechanochemical activation, i.e. an increase in the internal energy of the treated substances. Mechanochemistry refers to reactions, normally of solids induced by mechanical energy (Gomes et al., 2014), and mechanochemical reactions of organic compounds take place at the low milling energy (Takacs, 2014).

The intention of this paper was to introduce the results of using high-speed mills developed and manufactured by LAVARIS Ltd. for grinding of different biomass and minimising energy consumption. The present study has tested the possibility of using high-speed mills for disintegration of plant material in order to improve the pre-treatment and to expand the utilization of vast residual biomass produced in the agricultural sector, wood processing, forestry activities and other esially available biomass. The main research aim was to investigate an impact of using high-speed mills on a material moisture content and reduction of its particle size.

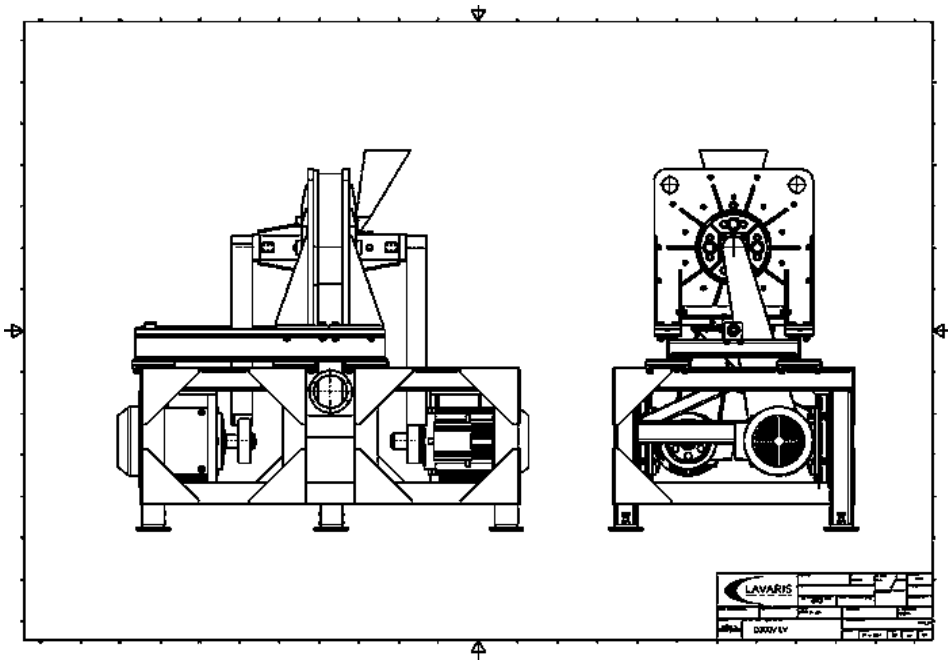


Figure 2. High-speed multilevel double rotors mill LAV 300/2R.

By Hajratwala (1982) the size reduction and heat amount produced in the high-speed milling process depend on the mill speed. The peripheral speed (v) is the speed that a point in the circumference moves per second and it was calculated for both machines by using the following equation:

$$v = \frac{\pi \times d \times n}{60}, \text{ m s}^{-1} \quad (1)$$

where $\pi - 3.14$; d – rotor disc diameter, m; n – revolutions per minute, min^{-1} .

In addition to this fact, the special and advanced construction of the tested high-speed mills, invented by LAVARIS Ltd., allowed to adjust the placements of the milling elements. Due to the flexibility in adjustable gaps between the milling elements it was possible to regulate a size of the space for the material flow, the intense of friction and the speed of the material's feeding. Thanks to the mentioned advantages, it was feasible to control the final size of output material and a temperature of the milling process.

One of the main parameters that characterize an efficient operation of a disintegrator is a particle size distribution (PSD) of the product obtained after the grinding process (Tumuluru et al., 2011; Chaloupková et al., 2016). The PSD of the input biomass, biomass after the first as well as second milling was determined by the vibrating screen method (EN ISO 17827-2, 2016) using a sieve shaker (AS 200, Retsch, Haan, Germany) with 30-min sieve shaking time for each repeated measurement and amplitude 3.0 mm g^{-1} . Therefore, for determination of particles size of the initial materials a set of calibrated sieves with the following mesh sizes was applied: 3.15 mm; 1.5 mm; 0.63 mm and the bottom pan. While determining the PSD of the materials obtained by the primary milling the sieves with the mesh sizes of 3.15 mm; 2.5 mm; 1.5 mm; 0.63 mm, including the bottom pan were selected. And, for the materials subjected to the secondary milling

the sieves with apertures of 2.5 mm; 1.5 mm; 1 mm; 0.63 mm; 0.50 mm; 0.25 mm and the bottom were used. Three tests (repetitions) were performed for each material and measurement; a captured sample weight on each sieve was calculated as a percentage of total weight expressed as arithmetic mean of three repetitions. Laboratory precision balance (KERN 572-35, Kern & Sohn GmbH, Balingen, Germany) with accuracy 0.01 g was used for weighting.

Moisture content of the input biomass, biomass after the first and second milling was determined in accordance with EN ISO 18134-3 (2015) by controlled drying of the sample in the laboratory oven (MEMMERT 100-800, Memmert GmbH + Co. KG, Schwabach, Germany) at 105 °C for several hours until the weight was constant in mass. The resulting moisture content on wet basis was calculated as the mean of duplicate determinations with respect to repeatability precision (i.e. difference between two individual results of each material sample was not more than 0.2% absolute) and using the following equation:

$$w = \frac{m_2 - m_3}{m_2 - m_1} \times 100, \text{wt\%} \quad (2)$$

where m_1 – mass of empty crucible, g; m_2 – mass of crucible with sample before drying, g; m_3 – mass of crucible with sample after drying, g.

RESULTS AND DISCUSSION

Based on the long-term experience of LAVARIS Ltd. in developing and operating high-speed mills, both machines were adjusted to the recommended position. The distance between the rotor and stator discs at the high-speed multilevel single rotor mill LAV 400/1R was 3 mm, thus the peripheral speed was found to be 163 m s⁻¹. For the high-speed multilevel double rotors mill LAV 300/2R the distance between both rotors was about 1.5 mm and the peripheral speed then 194 m s⁻¹.

Particle size distribution of tested materials including determination of PSD of input materials with initial fraction as well as PSD after first and second milling are presented at the Tables 1–2. It was obvious that the space between the rotor discs effects the final size of the treated material.

In case of herbaceous miscanthus more than 94% of initial particles were smaller than 3.15 mm, moreover more than half of the material was captured on the sieve with aperture of 1.5 mm, followed by the sieve of 0.63 mm and the bottom pan (Table 1). Almost identical results of PSD were obtained by Chaloupková et al. (2016) in case of *Miscanthus x giganteus*, which confirms similar structure of miscanthus species. Concerning PSD of pine sawdust initial fraction, the sieve analysis showed that over 81% of material's particles were smaller than 3.15 mm, where 65.74% of the material almost equally distributed between the sieves with apertures 1.5 and 0.63 mm (Table 2).

Tables 1 and 2 illustrate that the particle size was visibly reduced after the first milling. Almost 99% of miscanthus particles passed through the sieve with apertures of 2.5 mm, and moreover more than 87% of material was captured and equally divided between the sieve of 0.63 mm and the bottom pan. In case of pine sawdust more than 99% of particles were smaller than 3.15 mm and almost 60% of particles was captured on the sieve 0.63 mm, followed by the bottom pan.

Table 1. Particle size distribution of miscanthus biomass

Miscanthus sinensis								
Initial size			First milling			Second milling		
Sieve,			Sieve,			Sieve,		
mm	g	%	mm	g	%	mm	g	%
3.15	3.27	5.86	3.15	0.5	0.62	2.5	0.20	0.27
1.5	30.85	55.32	2.5	0.61	0.73	1.5	0.19	0.26
0.63	15.47	27.74	1.5	9.25	11.24	1.0	0.97	1.32
< 0.63	6.18	11.08	0.63	37.09	45.09	0.63	9.43	12.79
			< 0.63	34.81	42.32	0.50	3.04	4.12
						0.25	19.31	26.20
						<0.25	40.57	55.04
Total	55.77	100	Total	82.26	100	Total	73.71	100

Table 2. Particle size distribution of pine sawdust

Pine sawdust								
Initial size			First crushing			Second crushing		
Sieve,			Sieve,			Sieve,		
mm	g	%	mm	g	%	mm	g	%
3.15	15.97	18.60	3.15	0.51	0.59	2.5	1.22	1.72
1.5	25.78	30.05	2.5	2.49	2.87	1.5	0.32	0.45
0.63	30.63	35.69	1.5	7.44	8.57	1.0	4.77	6.74
<0.63	13.44	15.66	0.63	51.03	58.78	0.63	18.61	26.29
			<0.63	25.34	29.19	0.50	4.16	5.88
						0.25	19.83	28.01
						<0.25	21.88	30.91
Total	85.82	100		86.81	100		70.79	100

Second milling resulted in very fine particles. About 98% of miscanthus particles was smaller than 1 mm, and in case of pine sawdust smaller than 1.5 mm. Majority of miscanthus biomass (more than half) was captured on the bottom pan (< 0.25 mm), followed by the smallest sieve of 0.25 mm containing ¼ of the particles. About 60% of wood biomass was divided between the smallest sieve and the bottom pan. Moreover, in case of sawdust only minimal amount of particles (less than 2%) was found on the largest sieve of 2.5 mm, for miscanthus number of bigger particles than 1.5 mm was just negligible. Interesting phenomenon was monitored in case of the sieve with apertures 0.63 mm, where almost 13% of miscanthus biomass and twice higher amount of wood material was captured, but probably clogged. Sieve clogging during an application of the mechanical screening was previously observed by Igathinathane et al. (2009) and Glé et al. (2013).

As for example, modern and promising pyrolysis technology has high requirements on the size of an input material due to the extremely rapid heat transfer to a feedstock (Choi et al, 2012), and thus the size is listed among the main limitations for the majority of reactors (Trávníček et al., 2015). By Jouiad et al. (2015), Mohammed et al. (2015) and Wannapeera & Worasuwanarak (2015) the maximum size of a material's particles should be 2 mm or optimal size is 0.2–1.8 mm (Yorgun & Yildiz, 2015), even 0.5–1 mm (Henkel et al., 2016). The experimental results showed that pre-treatment of the materials by high-speed mills can satisfy these requirements.

Obtained results of moisture content are presented in the Table 3. As it can be seen, the initial moisture content of both materials was relatively high and that biomass is not suitable for efficient direct combustion or production, utilization and storage of densified biofuels like briquettes, pellets as well as use for pyrolysis process, etc. The abovementioned is based on the facts that: high moisture content has negative impact on solid biofuels properties, especially calorific value reached during the burning process (Huhtinen, 2005; Havrland et al., 2011; Ivanova et al., 2012) as well as reduction of the combustion device efficiency and a fuel efficiency (Černý et al., 2016); wet material is not bound well during densification (Muntean et al., 2017); decomposing microbial processes stop while moisture content is under 20% (Sladký & Hutla, 2000). According to Havrland et al. (2011) and Muntean et al. (2017) the proper moisture for biomass briquetting must not exceed 12–14%, depending on the technology. For the pyrolysis process it is important to pre-dry biomass to a lower moisture than 10% (Rogers & Brammer, 2012; Joubert et al., 2015), thus it will lead to a water reduction in pyrolysis products, mainly liquid one (Akhtar & Amin, 2012).

The results of the first milling showed the reduction of moisture content by 4.65% in case of miscanthus and 7.67% in case of pine sawdust (see Table 3), however the obtained moistures were still high for utilization. During the second milling the moisture content of both materials decreased significantly and resulted into the optimal values. Comparing with the first milling, the moisture of miscanthus dropped by 12.59% and by 20.86% in case of wood, which is equal to 17.24% and 28.53% moisture reduction in contrast with the initial moistures of miscanthus and pine sawdust, respectively. Biomass drying is usually a time consuming process, thus utilization of high-speed mills for coincident biomass drying provides a good solution to the time issue as well.

Finally, it is feasible to do a simple comparison between the tested high-speed milling technologies and the conventional systems of milling and drying in relation to the energy consumption. The engine power of commonly applied biomass crushers is about 22 kW and the production output varies between 400 to 1,000 (Deines & Pei, 2010). The engine power of typical drum dryer is 12–14 kW and hot air boiler 300–400 kW (Gigler et al, 2000; Li et al, 2012). So, both systems will need approximately 34–36 kW of electric engine power plus the energy for hot air boiler. Tested high-speed mill LAV 400/1R has maximum electric engine consumption of 10 kW and the second high-speed mill LAV 300/2R has maximum electric engine power of 32 kW. This comparison also shows the advantages of tested systems above the conventional ones.

CONCLUSIONS

The results unequivocally showed that during the milling of biomass by high-speed mills a significant reduction of moisture takes place. In case of miscanthus the moisture

Table 3. Comparison of moisture content of initial materials and materials after first and second milling

Material	Moisture content, wt%
Initial material	
<i>Miscanthus sinensis</i>	24.43
Pine sawdust	37.08
First crushing	
<i>Miscanthus sinensis</i>	19.78
Pine sawdust	29.41
Second crushing	
<i>Miscanthus sinensis</i>	7.19
Pine sawdust	8.55

content changed from 24.43% (input material) to 19.78% (after the first milling) and then to 7.19% (after the second milling). In case of pine sawdust the moisture reduction was even more obvious: from 37.08% to 29.41% and finally to 8.55%, respectively. Thus, required moisture content for biofuels' production and other utilizations was achieved.

The milling resulted in obtaining of very fine particles of tested biomass materials. The granulometry/sieve analysis show that:

- For herbaceous biomass of miscanthus, 61% of the initial material particle size was above 1.5 mm, after the first disintegration 87.4% particle size was smaller than 1.5 mm and after the second disintegration 81.2% particles size was below 0.5 mm.
- For pine wood sawdust, 49% of the initial material had particle size larger than 1.5 mm, after the first disintegration almost 88% particle size was below 1.5 mm and after the second disintegration 91% particle size was smaller than 1 mm, where 58.9% was below 0.5 mm.

Hence, the experimental tests showed that application of the manufactured high-speed mills with a special construction is a promising technological solution for improved biomass pre-treatment combining both effects, drying and grinding processes, which are typically very expensive and energy demanding operations.

As it was seen during the experiments, there are three factors which affect the treated material. The gap between milling discs has impact on the final size of the output material; beside the course of milling temperature as a result of a friction force inside the machine affects the material moisture. The rotors speed is another important factor, and with increasing rotor speed the output material size was smaller and the temperature was higher. These factors related to the operating conditions of the high-speed mills will be a subject of the next paper.

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