Acta Polytechnica **55**(2):113–122, 2015
doi:10.14311/AP.2015.55.0113

MECHANICAL DISINTEGRATION OF WHEAT STRAW USING A ROLLER-PLATE GRINDING SYSTEM WITH SHARP-EDGED SEGMENTS

Lukas Kratky*, Tomas Jirout

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Process Engineering, Technicka 4, 166 07 Prague 6, Czech Republic

* corresponding author: Lukas.Kratky@fs.cvut.cz

Abstract. Colloid mills and extruders are widely used for disintegrating wet fibrous biomass. However, their main disadvantages are a high energy requirement in the range of hundreds or thousands of kWh per ton of material, and the fact that they grind in process cycles. Efforts have therefore been made to design a new type of continuously operated grinder. Its disintegration principle uses a roller-plate grinding system with sharp-edged segments, where the compressive and shear forces combine to comminute the particles. Test experiments verified that the grinder disintegrates wet untreated straw to particles below 10 mm in an effective manner in a single pass, with an energy requirement of 50 kWh t^{-1} TS. A 23 % increase in biogas yield was achieved, leading to a net gain in electric energy of 310 kWh t^{-1} TS.

Keywords: biogas yield; energy requirement; retting mill; wheat straw.

1. Introduction

Biogas plants currently in operation are based on the treatment of lignocellulosic biomass, which can be found in materials such as agricultural and forestry wastes, municipal solid wastes, waste paper, wood, and energy crops. These lignocelluloses are generally composed of cellulose, hemicellulose, lignin, and organic and inorganic compounds. Hydrolytic, acidogenic and acetogenic microorganisms in an anaerobic batch subsequently transform cellulosic and hemicellulosic fractions through saccharides, alcohols and fatty acids into hydrogen, carbon dioxide and acetic acid, which are finally converted into biogas by methanogenic bacteria. However, the composite structure of native lignocellulosic materials makes them resistant to microbial attack. In his review [1], Pandey points out that the biodegradation of native untreated lignocelluloses is very slow, and that the extent of degradation is often low and does not exceed 20 %. The composite structure of lignocellulosic biomass must therefore be intensively disrupted and defibred in order to increase the accessibility of the cellulose and hemicellulose and the effectiveness of the hydrolysis [2]. A large number of pretreatments have been tested by many researchers. These methods can be broadly classified into physical, chemical, physicochemical, and biological processes [3]. A combination of two or more pretreatments is sometimes applied. The general aim of pretreatment is to change the properties of the biomass in order to prepare lignocelluloses for microbial attack. An effective and economical pretreatment method increases cellulose accessibility and enhances complete solubilisation of a polymer to monomer sugars without the formation of degradation products [4].

Mechanical pretreatment is the simplest technique for effectively disrupting the lignocellulose matrix. It improves the biodegradability of the native substrates by breaking large structures into shorter chains, thus making the biodegradable components more accessible to microorganisms. Mudhoo [5] reported that disintegration enhances methane production from 5 % to 25 %. In addition, Hendriks et al. [4] showed that the anaerobic digestion time.is reduced by 23–59 % when biomass is disintegrated. The impact of mechanical disintegration on biogas yield has been studied by many researchers [3,6,7,8]. Junling et al. [6] studied the effect of wheat straw particles on biogas yield and on residue production in anaerobic technology. The biogas tests were carried out with wheat straw lengths of 100, 50, and 10 mm under mesophilic conditions at a temperature of 35 °C. The test showed that the biogas yield increased with a decrease in particle size. Considering the biggest benefits in biogas yield, that the disintegration of wheat straw into particle sizes of 10 mm is more appropriate. Junling et al. [6] concluded that the biggest increase in biogas yield resulted from disintegrating wheat straw into particles 10 mm in size. Sharma et al. [7] studied the effect of wheat straw particle size on the efficiency of biogas digesters operating on agricultural and forest residues. The total biogas production of wheat straw increased with decreasing particle size. Sharma et al. [7] found that the total biogas production for particle sizes of 0.088, 0.40, 1.0, 6.0, and 30 mm was 362, 360, 350, 330, and 235 $Nm^3 t^{-1}$ TS, all with a volumetric concentration of methane in the biogas of 58 %. Based on the data mentioned above, it can be concluded that the biogas yield generally increases with decreasing particle size of the biomass. However, there are also lower limits for particle size. Izumi et al. [8] found that hydrolytic microorganisms are able to degrade cellulose and hemicellulose very effectively for fibrous food wastes less than 1 mm in length. However, they observed rapid generation of fatty acids during hydrolysis. This reduced the acidity of the fermentation batch, leading to the inhibition of methanogenesis. Moreover, a comparison of the biogas yields of 362 NmtTS for wheat straw particles of 0.088 mm and of 330 $\mathrm{Nm^3\,t^{-1}}$ TS for wheat straw particles of 1.0 mm [7] showed that there is only a 3 % increase in the biogas yield. This difference is negligible from the industrial point of view, and the efficient particle size of wheat straw in relation to biogas yield therefore ranges between 1–10 mm.

Although mechanical pretreatment has been shown to have a significant impact on enhancing biogas production, a major disadvantage of its use is the high energy requirement [9]. Schell and Hardwood [10] reported that mechanical disintegration itself can consume up to 33 % of the electricity required for the whole technology. Kratky and Jirout [9] reported that the energy requirement generally depends on machine variables, on the initial and final particle sizes, and on the amount of processing, the composition and the moisture content in the biomass. On the basis of experiments, Deines and Pei [11] generally concluded that the specific energy increases with a decrease in the final particle size. Smaller particle sizes tend to result in higher biofuel yield, but require more energy. To find the optimum particle size, it is important to know the relationships among particle size, energy demand and biogas yield. Knife, hammer, roll, colloid mills and combined extruder-colloid mill units are widely used for disintegrating lignocellulosic biomass [12]. Yu et al. [13] studied the energy requirements of hammer mills. Wheat straw with an initial moisture content of 8.3 % wet basis and 20–50 mm in length was used in the experiments. Using screen sizes of 0.794, 1.588, and 3.175 mm, they observed energy requirements of 51.55, 39.59, and 10.77 $\mathrm{kWh\,t^{-1}}$. The energy requirement for reducing wheat straw with a moisture content of 4–7 % wet basis using a hammer mill was also studied by Cadoche and Lopéz [14]. They found that the energy requirement for reducing straw from a particle size of 22.4 mm to 3.2, 2.5, and 1.6 mm using a hammer mill were 21, 29, and 42 $\mathrm{kWh\,t^{-1}}$, while for reducing straw from a particle size of 22.4 mm to 6.3, 2.5, and 1.6 mm using a knife mill, the energy requirement was 5.5, 6.4, and 7.5 $\mathrm{kWh\,t^{-1}}$. Hideno et al. [15] worked on determining and comparing the energy requirements for rice straw disintegration using a colloid mill and using a ball mill. The aim of their study was to reach a final particle size lower than 2 mm (the initial particle size is not mentioned in the paper. Using a ball mill, saccharide conversion of almost 90 % was achieved with a process time of 1 hour, with an energy demand of 30000 $\mathrm{kWh\,t^{-1}}$. For the colloid mill, saccharide conversion of almost 80 % was achieved after 10 processing cycles, with an energy demand of 1500 $\mathrm{kWh\,t^{-1}}$. Combined extruder-colloid mill disintegration units are the most effective size reduction machines for disintegrating wet fibrous materials. Sabourin [16] states that the typical energy requirement of this machine is 100–200 $\mathrm{kWh\,t^{-1}}$. If the disintegrated material is sprayed with a weak solution of sulphuric acid or nitric acid, the energy requirement usually decreases to 120–130 $\mathrm{kWh\,t^{-1}}$. According to previous data, hammer and knife mills are widely used in biomass size reduction technologies due to their low energy requirement in relation to particle size. However, their main disadvantage is when disintegrating biomass with a moisture content in excess of 20 wt% [9]. Wet material usually gets plugged in the drum sieve, so the material cannot pass through the sieve, and there is also a problem with achieving fine particle sizes. Colloid mills and extruders are the most widely used machines for disintegrating biomass with a moisture content in excess of 20 wt% [9]. However, when a wet disc mill is used, it makes the operation require high energy, and it is usually necessary to mill in processing cycles. It is usually not possible to achieve the required final particle size for subsequent processing in a single pass through these machines. This statement was endorsed by Diószegi et al. [17]. Diószegi et al. evaluated the efficiency of the Shark comminuting machine for disintegrating wheat straw particles 4 mm in size. This grinder works on the principle of the colloid mill. Its grinding chamber is composed of a rotating disc that exerts enormous shear forces on the particles in an aqueous batch at a concentration up to 2.5 wt%. The results showed strong dependence of the final particles on the number of processing cycles, the soaking time and the input sizes of the straw particles.

All materials with moisture over 20 wt% that are fed in large quantities into biogas technologies should be disintegrated in colloid mills or extruders. However, the energy requirements of these grinders are in the range of hundreds or thousands of kWh per ton of material, and the biomass must be ground in process cycles to achieve the required particle size. The size-reduction machinery presently operating at biogas plants is not capable of disintegrating wet fibrous biomass effectively. Efforts have therefore been made to develop a new type of grinder that can be used for continually reducing the size of wet fibrous biomass to the required particle sizes in a single pass through the grinder. Our paper presents tests carried out on the grinder for disintegrating wet fibrous biomass, verifying its efficiency through experiments aimed at quantifying its energy requirements in relation to particle size, and its impact on the structure of the straw and on biogas production.

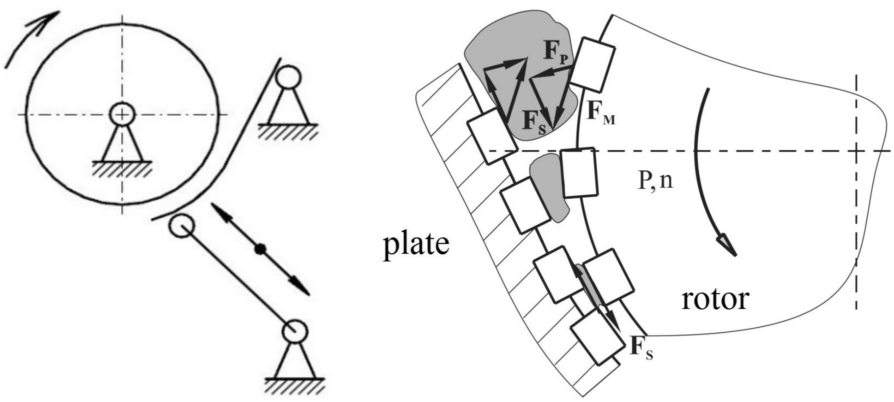

Figure 1. The principle of particle disintegration in a retting mill: scheme of the grinding system (left) [18], impact of the forces on a particle (right).

2. Materials and Methods

2.1. Retting mill

A new prototype of a pilot grinder for disintegrating wet fibrous biomass was developed in cooperation with the company Prokop Invest, see Figure 1. The idea of this grinder [18] is to combine crushing and cutting size reduction methods, i.e., to apply compressive and shear forces to the biomass particles. From the point of view of design, shear forces are easily generated in roller-roller or roller-plate grinding systems, while compressive forces can be generated by compressing particles between grinding segments that are fitted to both the roller and the plate. The roller-plate grinding system is more advantageous, because it is easier to design and there are lower investment costs for the equipment. Moreover, if the plate is appropriately curved, see Figure 1A, the length of the milling gap is extended. This geometrical modification ensures enough space for installing multiple rows of grinding segments and therefore a more intense effect of the shear forces on the raw material, see Figure 1B. After entering the grinding chamber, the biomass particles are first exposed to the impact of compressive forces F_P, and they are crushed. The reduced particles are subsequently fed into the milling gap, where they are exposed to shear forces F_S, and are sheared and defibred.

The basic design of the pilot grinder is shown in Figure 2. The milling chamber is formed by a horizontally placed roller (1) and a plate (3), which are placed in a cradle (2). The sharp-edged grinding segments are fitted in rows to the circumferential surface of the rotor. These grinding segments are placed in the middle row parallel to the axis of rotation, in which the outer rows are alternately inclined at an angle. This geometrical configuration ensures that the material is continuously pulled into the milling gap and is moved. The grinding plate (3) in its upper position is mounted in the rotating cradle (2) in the region of input neck of the material (4). The position of the grinding plate, i.e. the height of milling gap, is easily adjustable towards the rotor by screws (5) which support its lower portion. The grinding plate is also equipped with several rows of sharp-edged grinding segments. The rotor (1) is closed circumferentially from the lower edge of the grinding plate (3) to the input neck (4), by the drum sieve (6), which incorporates holes 5 mm in diameter. The control covers (7) are used as a control, or as openings for cleaning.

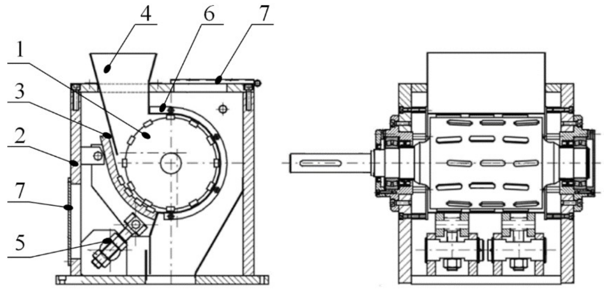

Figure 2. Design of a retting mill [19] (1–rotor, 2–cradle, 3–plate, 4–input neck, 5–adjustment screws, 6–drum sieve, 7–control cover).

The variable parameters of the grinder are the amount of biomass for processing, the gap size, the rotational roll speed, the flow rate and the temperature of the hot water. Hence, the effectiveness of the grinder is evaluated by the energy requirement for comminution, by the changes in microstructure, and also by biogas tests of the treated material. The energy requirement is determined on the basis of measurements of the total active power P_{ACTIVE} over time t by the PLA33C power line analyser. The mill is first run with no load, in order to establish a baseline for the total active power under no-load conditions (without wheat straw). Once the baseline has been recorded, wheat straw is milled under the adjusted process parameters. The measured parameters are also simultaneously recorded. To evaluate them, the dependence of total active power on time is recalculated to kilowatt-hours per ton. This means that the measured kilowatts per time period are converted to kilowatt-hours and are divided by the kilograms of milled biomass, which is converted into tons.

2.2. Test material

Wheat straw is one of the most common agricultural wastes, and is also a typical representative of lignocellulosic biomass. Its worldwide production has been estimated to be $611 \cdot 10^6\,\mathrm{t\,r^{-1}}$ [20], and it is mainly used in agriculture as a feed or for bedding, and also as an element in compost. It is also used in the pulp industry and as a feedstock in biogas plants. Wheat straw was therefore used in the experiments. The straw was cut by a harvester in the field, and was collected and stored in containers at ambient temperature in our laboratory. The straw was approximately 200 mm in length. It was characterized by an analysis of the total solids content (TS), the volatile solids content (VS), the chemical oxygen demand (COD), and its composition. The total solids content of the wheat straw was equal to 93 wt% and the volatile solids content was equal to 81 wt% TS. The total solids content was determined by standard drying of 5 samples in a Binder FD53 oven at a temperature of 105 °C up to constant mass of the samples. The volatile solids content was investigated by standard burning in an LE 09/11 furnace at a temperature of 550 °C up to constant mass of the samples. The mass of the material was measured using an SDC31 analytic balance. The chemical oxygen demand value for wheat straw was $978\,\mathrm{g\,kg^{-1}}$, i.e., $1051\,\mathrm{g\,kg^{-1}}$ TS. This was determined from dispersed suspension straw-distilled water by the dichromate micro method with spectrometric ending, see Section 2.4. The wheat straw composition was characterized by an analysis of cellulose, hemicellulose, lignin and ash, which was carried out by the thermo-gravimetric method [21], and by an elementary analysis in an Elementar Vario EL III. The tested wheat straw was composed of 34.1 wt% TS in cellulose; 37.0 wt% TS in hemicellulose content; 22.8 wt% TS in lignin, and 6.1 wt% TS in ash. An elementary analysis of the wheat straw showed that the amount of carbon was 39.2 wt% TS, the amount of hydrogen was 41.62 wt% TS, and the amount of oxygen was 5.22 wt% TS.

2.3. Chemical Oxygen Demand

The chemical oxygen demand (COD) of a homogeneous suspension was evaluated by the standardized dichromate semi-micro method with spectrophotometric ending, where Spectroquant No. 114541 cuvette tests were used. For the samples with large straw particles, mechanical disruption was first carried out in order to increase the homogeneity, but care was taken not to change the nature of the sample. Five parallel measurements were taken, and the result is the average of the measured values.

2.4. Biogas Tests

To evaluate the impact of mechanical disintegration on the biodegradability of the wheat straw and especially on the biogas yield, the so-called Biochemical Methane Potential test was performed for untreated and milled wheat straw, in accordance with the VDI 4630 European standard [22]. Anaerobic digesters were designed as glass bottles with a capacity of 120 ml, with gas-tight caps, where a volume of 80 ml represented an anaerobic batch and the remaining volume of 40 ml was the storage area for the biogas that was generated. The mixture of straw and inoculum was filled into the digesters and was incubated under mesophilic conditions at a constant temperature of 35 °C by placing it in a room with a controlled temperature. The initial loadings of inoculum were 0.3 and $0.5\,\mathrm{g\,g^{-1}}$ (COD of the tested material, VS of inoculum). The seeding sludge from the anaerobic digester of the wastewater treatment plant in Liberec (CZ) was used in these experiments. Its characteristics were as follows: total solids $31.4\,\mathrm{g\,l^{-1}}$; volatile solids $16.2\,\mathrm{g\,l^{-1}}$; volatile solids 52.1 wt%, and COD $25.2\,\mathrm{g\,l^{-1}}$. The digestion units were shaken by hand once a day. The increase in biogas yield was monitored on a daily basis after the sludge mixture had been agitated, except at the beginning of the test, when the increase in biogas volume was evaluated more frequently. The amount of biogas was determined by its displacement in a gas burette over a salt solution to prevent loss of CO_2 by absorption. The anaerobic digestion test was deemed completed when the volumetric changes were lower than 1 % of the total biogas volume. The quality of the biogas ($CH_4 + CO_2$) was analysed by a GC8000TOP gas chromatograph. All biogas production values are given under standard conditions (0 °C and 101.3 kPa). The volume of biogas at standard temperature and pressure conditions was calculated after corrections for the effects of room temperature and water vapour pressure.

2.5. Biodegradability

The evaluation of the biodegradability of the wheat straw was based on knowledge of its chemical oxygen demand. The theoretical methane production Y_{CH4TEOR}, which is defined by VDI4630 [22], was calculated according to Equation (e1). As soon as the volumetric methane content in the biogas was known, the total theoretical biogas production Y_{BGTEOR} was calculated according to Equation (e2). All of these results are given under standard conditions (0 °C and 101.3 kPa).

$$Y_{\mathrm{CH4TEOR}} = 350\,\mathrm{COD}, \tag{1}$$

$$Y_{\mathrm{BGTEOR}} = 350\,\mathrm{COD}\,\frac{100}{\mathrm{vol\%\,CH_4}}. \tag{2}$$

Based on Equation (e1), it can be concluded that 1 ton of added COD corresponds to $350\,\mathrm{Nm^3}$ of methane. Considering this relationship, biodegradability X was therefore defined as the ratio of net substrate biogas production YCH4 achieved in the experiments, to the theoretical biogas production:

$$X = \frac{Y_{\mathrm{CH4}}}{350}. \tag{3}$$

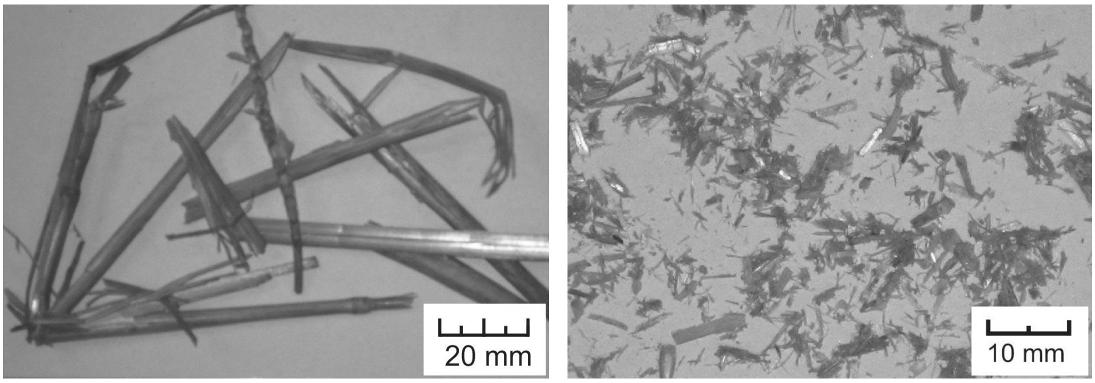

Figure 3. Macrostructure of wheat straw: A) before disintegration, B) after disintegration.

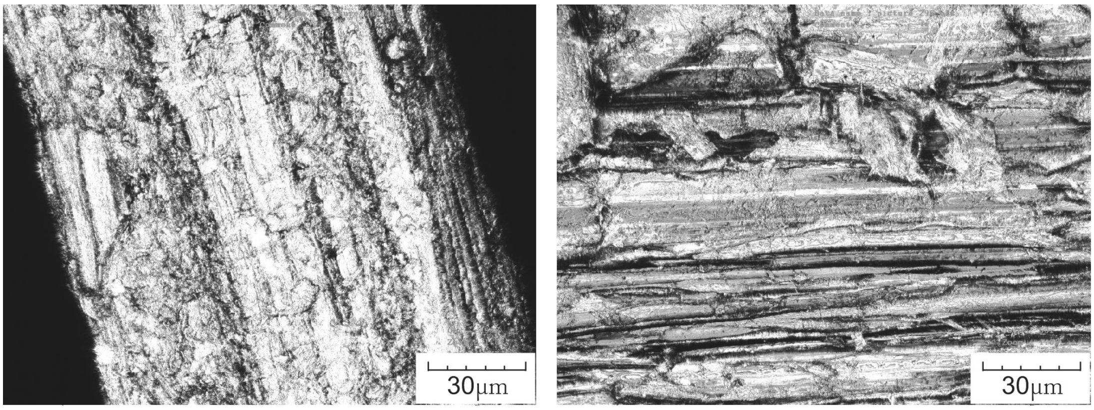

Figure 4. Microstructure of wheat straw: A) before disintegration, B) after disintegration.

3. Results and Discussion

3.1. Size reduction of wheat straw by the retting mill

Lignocellulosic biomass is usually inputted into biogas technology with moisture content above 20 wt%. It was therefore necessary to hydrate the wheat straw and to reach the state of the straw that is processed on an industrial scale. The tested amount of wheat straw was therefore first soaked in hot water at a temperature of 60 °C for a residence time of 10 min in order for it to be hydrated. In this way, a moisture content of 40 wt% was reached before it was used in the experiments.

The first test experiments with the newly-developed grinder were performed to find the optimum roll-sieve gap and the optimum rotational roll speed. The optimal roll-sieve gap and the rotational roll speed were considered to be the state in which straw does not accumulate in the roll-sieve gap and passes continuously through the holes of the sieve-drum, with a minimum residence time and a maximum reduction in size. The roll-sieve gap was changed in the range of 0.1–5 mm and a rotational roll speed in the range of 50–500 rpm during these experiments. The first major limiting process was the size of the milling gap. It was founded that its size must be as small as possible to achieve the most effective influence of the compressive forces. The second limiting process was associated with a rotational speed over 200 rpm. An accumulation of both untreated and disintegrated straw in the milling chamber was observed. This effect was definitely caused by the high centrifugal force values. The straw only circulated together with the roller, and the particles did not drop through the sieve-drum. Conversely, the third limiting process was associated with a rotational speed lower than 130 rpm, where clogging of the milling chamber with disintegrated straw was observed. The milling gap was gradually filled until it was entirely blocked. Due to the low centrifugal forces, there was no driving force to get the particles through the holes in the sieve. Therefore, on the basis of the experiments, a roller-sieve gap of 0.1 mm, and a roller speed in the range of 150–170 rpm are considered to be optimal settings for the grinder for wet wheat straw disintegration.

Deines and Pei [11] found that the specific energy increases with an increase in rotational speed. The energy requirement was therefore determined for the worst state, i.e., for the highest possible rotational speed. The process parameters during the experiments were as follows: roller-sieve gap 0.1 mm, roller speed 170 rpm, holes in the drum-sieve 5 mm, and continual manual feeding of wet straw into the milling chamber followed by continual spraying of water. A comparison of the initial and final particle sizes is depicted in Figure 3. Figure 3A shows that the initial particle sizes were up to approximately 200 mm,

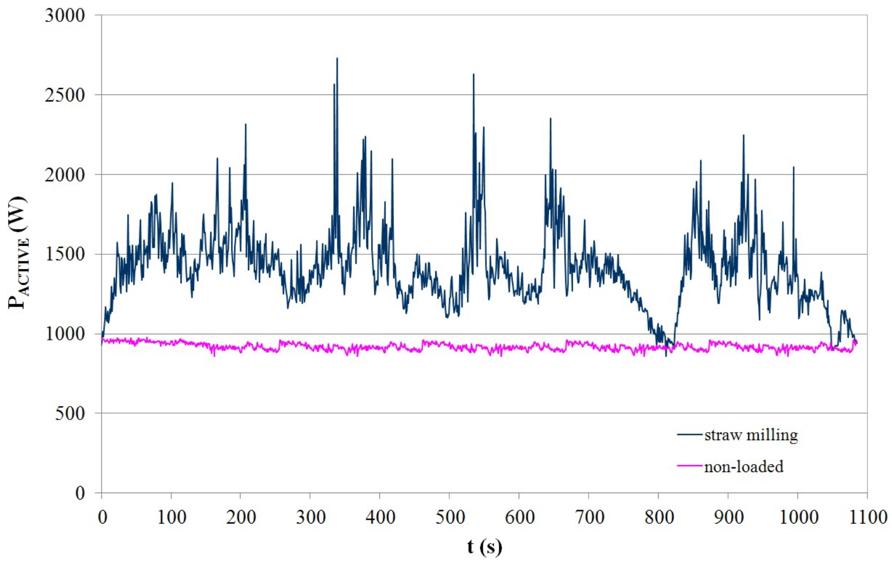

Figure 5. A typical measurement record – dependence of total active power over time.

and the particle sizes of the straw after disintegration were visually up to 10 mm, with a smooth surface, see Figure 3B. These results show that there is a demonstrably very high reduction in size. Moreover, detailed photos of the microstructure were obtained by scanning the sample with an Olympus LEXT OSL 3000 laser confocal microscope. These snapshots are depicted in Figure 4. As expected, the microstructure of the untreated wheat straw, see Figure 4A, was presented as a compact lignocellulosic matrix. However, a comparison of the structure of the untreated and treated straw shows that the structure after milling is very well-disrupted, see Figure 4B. The cellulosic fibres and significant ruptures in the structure are clearly visible. Both of these effects could have a strong effect on the digestibility of the wheat straw, and there is great potential for increasing its biodegradability and also the biogas production.

A typical record of measurements of the energy requirements for mechanical disintegration by a retting mill is plotted in Figure 5. It shows the dependence of total active power on time for a 5 kg amount of processed wet wheat straw. Using the trapezoidal method of numerical integration to dependence of total active power on time, it was calculated statistically that the energy requirement for disintegrating wet wheat straw by a retting mill with specific production of $120\,\mathrm{kg\,h^{-1}\,m^{-1}}$ was $30 \pm 3\,\mathrm{kWh\,t^{-1}}$, i.e., $72\,\mathrm{kg\,TS\,h^{-1}\,m^{-1}}$, with an energy demand of $50 \pm 5\,\mathrm{kWh\,t^{-1}}$ TS. The peaks in Figure 5 were caused by manual feeding of wheat straw into the milling chamber of the retting mill. The energy requirement of $10\,\mathrm{kWh\,t^{-1}}$ TS, which covers the passive resistance of the retting mill, must also be taken in account. It was determined on the basis of the minimum rotational speed when the roller began to revolve. The energy requirement of a retting mill is very close to the energy requirement of a hammer mill [14], which is 20–$42\,\mathrm{kWh\,t^{-1}}$ to produce final particle sizes of 3.2–1.6 mm. A crucial difference between the energy requirements for a retting mill and for a hammer mill is that the retting mill disintegrated wet wheat straw with 40 wt% moisture, while the hammer mill disintegrated dry wheat straw with 4–7 wt% moisture. The grinding principle of the hammer mill is based on the dynamic impact of compressive forces on dry brittle biomass particles between grinding segments. The hammer mill is therefore able to grind only biomass with a moisture content up to 15 % in an energy-efficient manner. The reason for this is that with increasing moisture there is a decrease in the elastic modulus of biomass particles. There is therefore a decrease in the impact of the compressive forces, the biomass particles are more elastic, and this makes the particles resistant to cutting. Hammer mills can be used for comminuting lignocelluloses with a moisture content of above 10–15 % (wb). However, the drum screen can become plugged, and it is therefore difficult to produce final particle sizes of 1–2 mm. However, all experiments were carried out with straw with a 40 wt% moisture content. The energy requirement must therefore be compared with the energy requirements of machines that are used for milling wet fibrous materials, i.e. ball mills, colloid mills or extruders. The energy demand is typically $30000\,\mathrm{kWh\,t^{-1}}$ to produce particle sizes below 2 mm for a ball mill [15], $1500\,\mathrm{kWh\,t^{-1}}$ to produce particle sizes below 2 mm for a colloid mill [15], and $200\,\mathrm{kWh\,t^{-1}}$ for a combined colloid mill and extruder [16]. These high values are caused by the need to grind in cycles – due to the longer grinding time there is a higher energy requirement. If the energy requirement of a retting mill, i.e., $50\,\mathrm{kWh\,t^{-1}}$ TS, is compared with these values, it is clear that the energy required for a retting mill to produce particle sizes of the same order is significantly lower than for widely-used commercial machines. There is also a

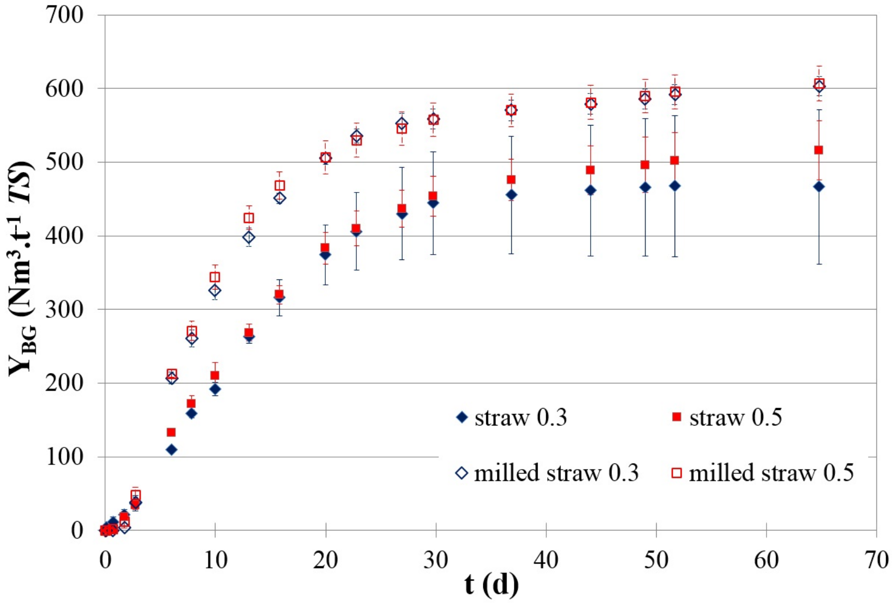

Figure 6. Dependence of specific biogas production over time related to TS.

Sample/loading	Specific production ($Nm^3\,t^{-1}$ COD)		X (%)
	$Y_{BG(AV)}$	$Y_{CH4(AV)}$	
Straw 0.3	445 ± 100	245 ± 55	70 ± 16
Straw 0.5	477 ± 37	241 ± 18	69 ± 05
Average	461 ± 70	243 ± 36	69 ± 10
Milled straw 0.3	491 ± 11	278 ± 6	79 ± 2
Milled straw 0.5	495 ± 19	264 ± 10	75 ± 3
Average	493 ± 14	271 ± 11	77 ± 3

Table 1. Specific biogas/methane production related to $Nm^3\,t^{-1}$ COD.

Sample/loading	specific production ($Nm^3\,t^{-1}$ TS)	
	$Y_{BG(AV)}$	$Y_{CH4(AV)}$
Straw 0.3	467 ± 105	277 ± 62
Straw 0.5	516 ± 40	273 ± 21
Average	491 ± 76	275 ± 41
Milled straw 0.3	603 ± 13	349 ± 8
Milled straw 0.5	607 ± 23	337 ± 12
Average	605 ± 17	343 ± 11

Table 2. Specific biogas/methane production related to $Nm^3\,t^{-1}$ TS.

significant difference that is in proportion to the size of the input/output particles. Commercial devices always require primary crushing and grinding of raw materials in cycles, while the wheat straw in the retting mill was milled without any preliminary crushing, and all in continuous mode.

3.2. Impact of Mechanical Disintegration on Biogas Production

The results of experiments obtained after 65 days of digestion are presented in Figure 6, in Figure 7, in Figure 8, in Table 1 and finally in Table 2. The specific biogas yields, expressed as Nm^3 per kg COD added or Nm^3 per kg TS added, were determined by plotting the cumulative biogas production over time. Firstly, all measured data was recalculated to standard conditions of dry gas. To evaluate net biogas production, the biogas production of inoculum was subtracted from the total biogas production of untreated and milled straw.

These results and calculations show a clear increase in biogas production and also in biodegradability. The average total biogas yield of untreated straw was determined as $491 \pm 76\,Nm^3\,t^{-1}$ TS, while an average total biogas yield of $605 \pm 17\,Nm^3\,t^{-1}$ TS was achieved for disintegrated straw, i.e., a 23 % increase in the biogas yield. These results fully correspond with experimental data published in [6,7]. The results presented by both research teams indicate that that disintegrating biomass to sizes of 1—10 mm increases the biogas yield by 20–40 %. However, the results for untreated straw show that there are higher standard deviation values for loading straw-inoculum and especially for loading 0.3, see Figure 6. These results were caused by the digesters getting filled with non-homogeneous straw, which had to be cut into small pieces due to its length in relation to the dimensions of the digesters. Filling the digesters with straw of different sizes caused differences in biogas production. The total methane yield was determined as a recalculation of the daily biogas production, which was multiplied

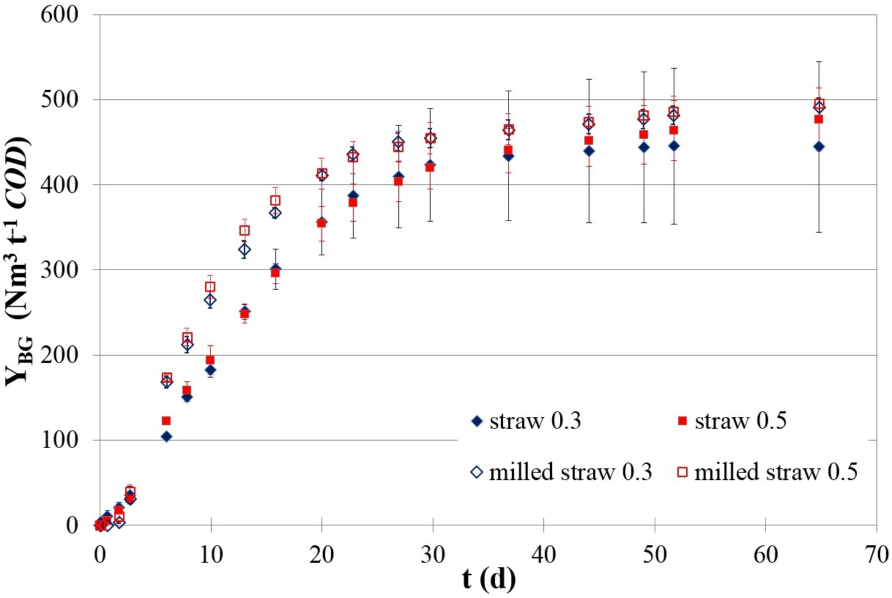

FIGURE 7. Dependence of specific biogas production over time related to COD.

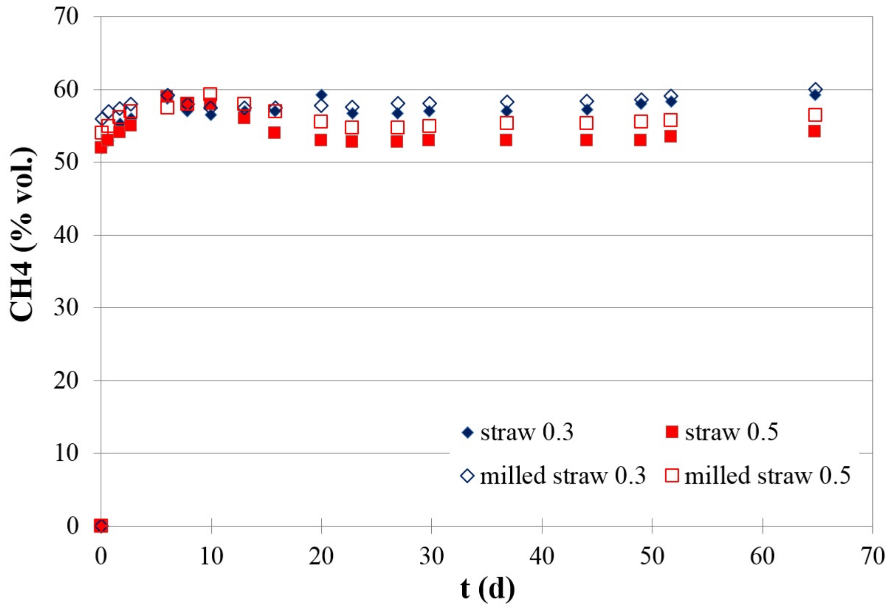

FIGURE 8. Dependence of volumetric methane content in biogas over time.

by the methane content (see Figure 7). On the basis of this data and using Equation (3), it was calculated that the biodegradability of the untreated wheat straw was $69 \pm 10\,\%$ and the biodegradability of the milled wheat straw was $77 \pm 3\,\%$, i.e., there was a 12 % increase in biodegradability.

3.3. OVERALL ENERGY BALANCE OF SIZE REDUCTION BY THE GRINDER AT THE BIOGAS PLANT

Combined heat and power generators (CHP) are the most widely-used gas processing equipment in biogas plants. The average electrical efficiency value of CHP is 38 %, and the average heat efficiency value of CHP is 47 % [23]. Taking into account these efficiencies, the measured average specific methane production values in Tab.1, and the inferior calorific value of methane being $9.94\,\mathrm{kWh\,Nm^{-3}}$ [23], it was determined that the electrical energy produced by CHP is equal to $930\,\mathrm{kWh\,t^{-1}}$ TS for untreated straw and $1300\,\mathrm{kWh\,t^{-1}}$ TS for disintegrated wheat straw, i.e., there is a difference of $370\,\mathrm{kWh_E\,t^{-1}}$ TS between them. Subtracting the amount of energy required by the grinder, i.e., $50\,\mathrm{kWh\,t^{-1}}$ TS, and the energy to break the passive resistance, i.e., $50\,\mathrm{kWh\,t^{-1}}$ TS, the net profit in electric energy Δ_{ESP} is equal to $310\,\mathrm{kWh\,t^{-1}}$ TS. In addition, heat is also generated in CHP by combustion of the biomethane that is generated. The heat that is produced amounts to $1140\,\mathrm{kWh\,t^{-1}}$ TS for untreated straw and $1600\,\mathrm{kWh\,t^{-1}}$ TS for disintegrated straw. Mechanical disintegration therefore also increases the heat profit

Wheat straw	Input	Output		Δ_{ESP}	Δ_{HSP}
	Q_{RT}	Q_{EP}	Q_{HP}		
Untreated	0	930	1140	ref	ref
Disintegrated	50	1300	1600	310	460

TABLE 3. Energy balance for pretreatment (all values in $kWh\,t^{-1}$ TS).

by 460 $kWh\,t^{-1}$ TS, i.e., by 40 %.

$$Q_{EP} = \eta_E q_{CH4} Y_{CH4AV} \quad (4)$$

$$Q_{HP} = \eta_H q_{CH4} Y_{CH4AV} \quad (5)$$

Mechanical disintegration of fibrous materials also has a significant impact on the energy requirement for the whole biogas technology. Kratky and Jirout [24] studied the impact of hydration and mechanical disintegration of wheat straw on the specific power needed for sufficient mixing of the fermenter batch that was formed by untreated/untreated hydrated/milled hydrated straw in water. It was concluded that both straw hydration and mechanical disintegration significantly improve the homogeneity and the pumpability of the fermenter batch. The experimental data verifiably ensured a 50 % decrease in specific power due to straw hydration and a 75 % reduction due to straw hydration and mechanical disintegration. Hydration of lignocellulosic biomass and mechanical disintegration therefore decreases the energy requirements of the mixing equipment, the pumps and the conveyers, leading to a decrease in the energy requirement for the whole technology and a decrease in operating costs for electric energy.

3.4. Scale-up of the retting mill

The grinder that has been developed is a continually milling pilot machine. For use in industrial applications, the methodology for the scale-up rules must be defined. The disintegration principle of the grinder is based on the mutual impact of the compressive and shear forces on a particle, These forces are derived according to the geometry of the retting mill (the diameter of the roller, the geometry of the plate, the geometry and the arrangement of the grinding segments) and the process parameters (revolutions, torque, size of the milling gap). It is assumed that it is necessary to achieve the same force effects on a particle in a model and in an industrial version of the grinder. If the geometric similarity of the machines is maintained, it is assumed that the productivity of the grinder should be scaled by increasing the diameter and the length of the roller. The rotational roller speed is assumed to be transferred according to:

$$n_{IN} = n_{LAB} \left(\frac{D_{LAB}}{D_{IN}} \right)^A . \quad (6)$$

If the compressive force is kept constant during scale-up, i.e., the theorem of constant circumferential speed, the value of parameter A is equal to 1. However, if the shear force is maintained constant, i.e., the theorem of constant specific power, then the value of A is equal to 2/3. For safe scaling, it is recommended to consider higher revolutions, and it is therefore better to use the theory of maintaining the compressive force with the value of A equal to 1.

4. Conclusions

Mechanical disintegration is an effective preliminary step resulting in an increase in biogas yield and in the biodegradability of lignocellulosic biomass. Grinders presently operating at biofuel plants do not reduce various species of biomass, particularly lignocellulosic biomass, in an economical and effective manner. A new grinder was therefore developed to disintegrate wet fibrous biomass effectively. The test experiments showed that the machine is highly efficient in disintegrating wet wheat straw. The machine is able continuously to disintegrate wet straw 200 mm in length to particles less than 10 mm in length, with an energy requirement of 50 $kWh\,t^{-1}$ TS, while a 23 % increase in the biogas yield was achieved due to the disintegration process. This led to a net profit in electric energy of 310 $kWh\,t^{-1}$ TS. All these results clearly indicate that the grinder has great potential as a practical mechanical technique for economical and effective pretreatment of fibrous biomass in biofuel technologies.

Acknowledgements

This work was supported by the Grant Agency of the Czech Technical University in Prague, Grant No. SGS14/60 and No.SGS15/067.

List of symbols

A constant [–]
CH_4 volumetric concentration of methane in biogas [vol%]
CHP combined heat and power generator COD chemical oxygen demand $[g\,l^{-1}]$
D_{IN} external diameter of roll [m]
D_{LAB} external diameter of roll [m]
F_M tangential force [N]
F_P compressive force [N]
F_S shear force [N]
n_{IN} rotational roll speed of an industrial mill $[s^{-1}]$
n_{LAB} rotational roll speed of an industrial mill $[s^{-1}]$
P power of a retting mill [W]
P_{ACTIVE} active power of a retting mill [W]
q_{CH4} inferior calorific heat of methane $[kWh\,Nm^{-3}]$
Q_{EP} produced electric energy $[kWh\,t^{-1}\,TS]$
Q_{HP} produced heat $[kWh\,t^{-1}\,TS]$
Q_{RT} supplied electric energy of a retting mill $[kWh\,t^{-1}\,TS]$
r_{xBP} specific biogas production rate $[Nm^3\,t^{-1}\,h^{-1}\,TS]$
t time [s]
TS total solids [wt%]
VS volatile solids [wt%]

w_{ANORG} ash content [wt%]
X biodegradability [1]
Y_{BG} specific cumulative biogas production $\left[\mathrm{Nm^3\,t^{-1}\,TS}\right]$
Y_{BGAV} average specific cumulative biogas production $\left[\mathrm{Nm^3\,t^{-1}\,TS}\right]$
Y_{BGTEOR} theoretical biogas production $\left[\mathrm{Nm^3\,t^{-1}\,COD}\right]$
Y_{CH4} specific cumulative methane production $\left[\mathrm{Nm^3\,t^{-1}\,TS}\right]$
Y_{CH4AV} specific cumulative methane production $\left[\mathrm{Nm^3\,t^{-1}\,TS}\right]$
Y_{CH4TEOR} theoretical methane production $\left[\mathrm{Nm^3\,t^{-1}\,COD}\right]$
Δ_{ESP} difference between produced and supplied electric energy $[\mathrm{kWh\,t^{-1}\,TS}]$
Δ_{HSP} difference between produced and supplied heat $\left[\mathrm{kWh\,t^{-1}\,TS}\right]$
η_{E} electric efficiency of CHP [1]
η_{H} electric efficiency of CHP [1]

References

[1] Pandey, A.: Handbook of plant-based biofuels. Boca Raton: CRC Press; 2009, ISBN 978-1-56022-175-3, 297 p.

[2] Vidal, B.C., Dien, B.S., Ting, K.C., Singh, V.: Influence of Particle Size on Lignocellulose Conversion – A Review. Applied Biochemistry and Biotechnology, 164, 2011, p. 1405-1421. DOI: 10.1007/s12010-011-9221-3

[3] Mosier, N., Wyman, Ch., Dale, B., Elander, R., Lee, YY., Holtzaplle, M., Landisch, M.: Features of promising technologies for pretreatment of lignocellulosic biomass. Bioresource Technology, 96, 2005, p. 673 - 686. DOI:10.1016/j.biortech.2004.06.025

[4] Hendriks, A., Zeeman, G.: Pretreatments to enhance the digestibility of lignocellulosic biomass. Bioresource Technology, 100, 2009, p. 10-18. DOI: 10.1016/j.biortech.2008.05.027

[5] Mudhoo, A.: Biogas Production: Pretreatment Methods in Anaerobic Digestion, Massachusetts: Scrivener Publishing LLC; 2012, ISBN 978-1-118-06285-2, 352 p.

[6] Junling, N., Yupeng, H., Quanguo, Z.: Effect of different comminution degree on the mesophilic and dry anaerobic fermentation of wheat straw. Acta Energiae Solaris Sinica, 32(11), 2011, p. 1683-1686.

[7] Sharma, S.K., Mishra, I.M., Sharma, M.P., Saini, J.S.: Effect of particle size on biogas generation from biomass residues. Biomass, 17, 1988, p. 251-263. DOI:10.1016/0144-4565(88)90107-2

[8] Izumi, K., Okishio, Y., Nagao, N., Niwa, Ch., Yamamoto, S., Toda, T.: Effect of particle size on anaerobic digestion of food waste. International Biodeterioration and Biodegradation, 64, 2010, p. 601-608. DOI:10.1016/j.ibiod.2010.06.013

[9] Kratky, L., Jirout, T.: Biomass size reduction machines for enhancing biogas production. Chemical Engineering and Technology, 34 (3), 2011, p. 391-399. DOI: 10.1002/ceat.201000357

[10] Schell, D.J., Hardwood, Ch.: Milling of lignocellulosic biomass. Applied Biochemistry and Biotechnology, 45-46(1), 1994, p. 159-168. DOI:10.1007/BF02941795

[11] Deines, T.W., Pei, Z.J.: Power consumption study in knife milling of wheat straw. Transactions of Manufacturing Research, 38, 2010, p. 191-196.

[12] Kratky, L., Jirout, T.: Energy-efficient size reduction technology for wet fibrous biomass treatment in industrial biofuel technologies. Chemical Engineering and Technology, 37(10), 2014, p. 1-9. DOI: 10.1002/ceat.201400243

[13] Yu, M., Womac, A.R., Pordesimo, L.O.: Review of biomass size reduction technology. In: ASAE Annual International Meeting, Las Vegas, USA, 27–30 July 2003, p. 1-12.

[14] Cadoche, L., Lopez, G.D.: Assessment of size reduction as a preliminary step in the production of ethanol from lignocellulosic wastes. Biological Wastes, 30, 1989, p. 153-157. DOI:10.1016/0269-7483(89)90069-4

[15] Hideno, A., Inoue, H., Tsukahara, K., Fujimoto, S., Minowa, T., Inoue, S., Endo, T., Sawayama, S.: Wet disk milling pretreatment without sulfuric acid for enzymatic hydrolysis of rice straw. Bioresource Technology, 100, 2009, p. 2706-2711. DOI:10.1016/j.biortech.2008.12.057

[16] Sabourin, M.J.: High defibrization pretreatment process for mechanical refining. [Patent]. US Patents, US 20080066877A, 2008-03-20.

[17] Diószegi, M.B, Horváth, M., Drégelyi-Kiss, Á.: Experimental design and study of shear technology for biomass comminuting. Applied Mechanics and Materials, 564, 2014, p. 555-559. DOI: 10.4028/www.scientific.net/AMM.564.555.

[18] Nalezenec, J., Jirout, T. (supervisor): Návrh nového typu macerátoru pro bioplynové stanice. Diploma Thesis, CTU in Prague, Faculty of Mechanical Engineering, Department of Process Engineering, 2012.

[19] Slabý, F., Nalezenec, J., Krátký, L., Maroušek J.: Retting mill. [Patent]. Industrial Property Office of Czech Republic, 26080, 2013-11-11.

[20] Ruiz, H.A., Ruzene, D.S., Silva, P.D., Macieira da Silva, F.F., Vicente, A.A. and Teixeira, J.A.: Development and Characterization of an Environmentally Friendly Process Sequence (Autohydrolysis and Organosolv) for wheat straw delignification. Applied Biochemistry and Biotechnology, 164, 2011, p.629-641. DOI: 10.1007/s12010-011-9163-9

[21] Sulc, R., Kratky, L.: Characterization of wheat straw pretreatment by thermo-gravimetric method. Inzynieria i Aparatura Chemiczna, 3, 2013, p. 264-265.

[22] VDI 4630. Fermentation of organic materials – characteristic of the substrate, sampling, collection of material data, fermentation tests. Verein Deutscher Ingenieure, 2006, ICS: 13.030.30.

[23] Deublein D, Steinhauser A. Biogas from Waste and Renewable Resources. Wiley VCH Verlag GmbH & Co. KGaA, Weinheim, 2011, ISBN 978-3-527-32798-0, 550 p.

[24] Krátký, L., Jirout, T.: Improving specific power consumption for mechanical mixing of feedstock in biogas fermenter by mechanical disintegration of lignocellulosic biomass. Acta Polytechnica, 54(5), 2014, p. 325-332. DOI:10.14311/AP.2014.54.0325