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The effect of mechanical disintegration on the biodegradability of wheat straw

Introduction

Wheat straw is the major crop residue in Europe and the second largest agricultural residue in the world [*Mudhoo, 2012*]. The advantage of exploiting wheat straw for various applications is that it is available in considerable quantity and at low-cost. Thus, wheat straw is considered to be one of the best options for increasing the biogas production through biomass digestion. Wheat straw is generally composed of cellulose, hemicellulose, lignin and wide variety of organic and inorganic compounds. Both cellulosic and hemicellulosic fractions are converted to monosaccharides that can be subsequently fermented to biogas. However, the inherent properties caused by composite structure make them resistant against enzymatic attack. Untreated wheat straw gives very low and commercially unattractive biodegradation yields 10÷30% [*Hendriks and Zeeman, 2009*]. Hence, pretreatment of biomass is an essential step in order to increase cellulose and hemicellulose accessibility and hydrolysis effectivity.

Mechanical pretreatment is almost always applied before any other kind of pretreatment. Decrease in particle size results in an increase of the available specific surface area and reduction of polymerization degree [*Mosier et al., 2005*]. Milling enhances biogas production from 5 to 25% [*Mudhoo A., 2012*] but also reduces digestion time by 23÷59% [*Hendriks and Zeeman, 2009*]. *Junling et al*. [*2011*] have studied the effect of different comminution degree on biogas and residue production by mesophilic fermentation. The results have verified that biogas yield increases with decreasing particle size. Based on the experiments, *Junling et al.* [*2011*] concluded that disintegration of wheat straw to particle sizes lower than 10 mm is the effective particle size in order to reach efficient biodegradability. *Sharma et al.* [*1988*] investigated that the total biogas production for particle sizes 0.088 mm, 0.40 mm, 1.0 mm, 6.0 mm, and 30 mm were 362, 360, 350, 330 and 235 litres·kg^{-1} of total solids under standard conditions, all with the quality 58% vol. of methane.

Nevertheless energy requirement of pretreatment could affect the overall energy balance of biomass conversion processes. This operation usually consumes about 33% of total electrical demand [*Kratky and Jirout, 2011*]. *Kratky and Jirout* [*2011*] also concluded that the energy demand depends on machine variables, initial and final particle sizes and biomass characteristics, namely processing amount, composition and moisture content. The specific energy generally increases with decrease in final particle size [*Deines and Pei, 2010*]. Smaller particle sizes tend to result in higher biofuel yield but require higher energy demand. As for machines, knife, hammer, roll and colloid mills are commonly used for disintegration of lignocellulosic biomass [*Kratky and Jirout, 2011*]. *Yu et al.* [*2003*] have investigated the energy demand of hammer mill. The specific energy demands for grinding of 20÷50 mm long wheat straw with initial moisture content 8.3% wet basis (wb) using screen sizes 0.794, 1.588, and 3.175 were 51.55, 39.59, and 10.77 kWh·t^{-1}. *Cadoche and Lopez* [*1989*] have tested knife and hammer milling of wheat straw with moisture content of 4-7% (wb). The energy demand to reduce straw from particle size 22.4 mm to 3.2 mm, 2.5 mm, 1.6 mm by hammer mill were 21, 29 and 42 kWh·t^{-1} while to reduce straw from particle size 22.4 mm to 6.3 mm, 2.5 mm, 1.6 mm by knife mill were 5.5, 6.4 and 7.5 kWh·t^{-1}. *Hideno et al.* [*2009*] compared the energy requirements of colloid and ball mills for rice straw disintegration to reach final particle size lower than 2 mm (initial particle size is not mentioned). Using ball mill, the saccharides conversion with process time 1 h was practically 90% and its energy demand was 30 000 kWh·t^{-1}. As for using wet disc mill, the saccharides conversion was practically 80% after 10 processing cycles and its energy demand only 1500 kWh·t^{-1}.

The objectives of this paper were to test macerator and to evaluate its energy demand related to particle size and its effectiveness by evaluation of increase in biogas production and biodegradability.

Methods

Raw material

Untreated wheat straw was used in experiments. This straw was cut only by combine on field, collected and stored indoors in containers at ambient temperature. The total solids content was determined by drying of samples in oven (KBC-25W) overnight at temperature 105°C, whereas the volatile solids content was investigated by burning in furnace (LE 09/11) at temperature 550°C up to constant mass of samples measured by analytic balance SDC31.The total solid content (TS) was determined to be 93% by weight (wt), the volatile solid content (VS) was 89% wt. and COD (chemical oxygen demand) was 978 g COD·kg^{-1}. Typical wheat straw contains cellulose in range 33÷50% of dry matter (*DM)*, hemicellulose 24÷35.5% *DM* and lignin in range 8.9÷17.3% *DM* [*Garrote et al., 1999*].

Macerator

The new prototype of mill, named as MACERATOR, has being tested, see Fig. 1. This machine was developed in cooperation with the company *Prokop Invest* [*2012*] and more information about this prototype can be found in [*Nalezenec, 2012*].

The determination of energy requirement of comminution is based on the measurement of total active power P_{ACTIVE} in time t by power line analyser PLA33C. First the mill runs with no load to get a baseline about the total active power under the no-load condition (without wheat straw). Once the baseline is recorded, wheat straw is milled under adjusted process parameters. Wheat straw is manually fed into the mill where is continuously soaked by spraying of water. Measured parameters are also simultaneously recorded. As for their evaluation, the dependence of total active power on time is recalculated to kilowatt-hours per ton [kWh·t^{-1}].

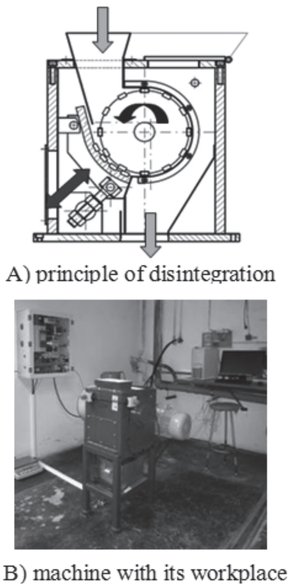

Fig. 1. Macerator [*Prokop Invest, 2012*; *Nalezenec, 2012*]

Biogas tests

The biogas tests with untreated and milled wheat straw were carried out in accordance with European standard [*VDI 4630, 2006*]. In detail, 9 glass batch digesters with capacity of 120 ml were used. These bottles were filled up with mixture of tested waste with seeding sludge from the biogas plant in Liberec (CZ) to volume 80 ml. The analyzed variants and inoculum were weighed out in a ratio of 1:3 (based on COD). The digesters were incubated under mesophilic conditions at constant temperature of 35°C. The amount of biogas quantity was monitored daily. The methane content was analyzed by gas chromatography. Biogas and methane production are given in norm liters (0°C and 101.3 kPa).

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Results and discussion

Energy requirement of mechanical disintegration

Before the disintegration the amount of wheat straw was soaked in hot water with temperature 40°C to be sucked. Thus the moisture content 40% wt. was reached before milling. This wet wheat straw was manually fed into the mill and continuously sprayed by water from water main. The first test experiment deals with the finding of an optimal rotational roll speed. The optimal roll-sieve gap and rotational roll speed were proclaimed to be the state that the straw does not accumulate in roll-sieve gap and continuously goes away through the holes maximum size reduction. Based on tests, the optimal roll-sieve gap was 0.1 mm and the roll speed was determined in range 150÷170 rpm.

Therefore the energy requirement and biogas test were determined for this configuration: roll-sieve gap 0.1 mm, roll speed 170 rpm, continual manual feeding of wet straw into the milling chamber and continual spraying by water. The comparison of the initial and final particle sizes is shown in Fig.2. The initial particles were approximately up to 20 cm, see Fig.2A, whereas the particle sizes of straw after disintegration were visually up to 10 mm with a smooth surface, see Fig. 2B. Thus there is demonstrably a high reduction in size. Using trapezoidal method of numerical integration to measured dependence of total active power on time, it was calculated that the energy requirement was only 29 kWh·t^{-1} of wet straw. If this value is compared to energy demand of wet disc milling, discussed in introduction, it is clear that this new type of machine shows much lower energy demand. This value is comparable to specific energy demanding by knife or hammer mills.

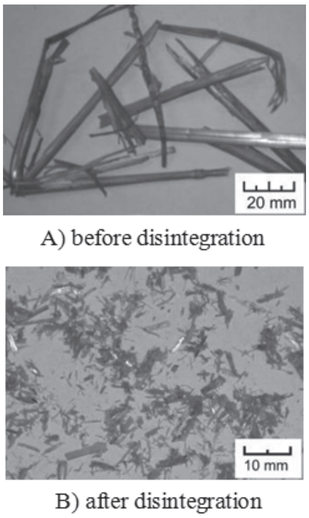

Fig. 2. Dried final particle size of wheat straw

Impact of disintegration on biogas production

The results of biogas test are depicted in Fig. 3. Firstly, all measured data were recalculated to standard conditions of dry gas. To evaluate the net biogas production, the biogas production of inoculum was subtracted from the total biogas production of non-treated and milled straw. The methane yield was approximately constant with value 57.7±1.1% vol. in the course of experiments.

As it is shown in Fig. 3, the total biogas production of milled straw is higher than the biogas production of non-treated straw. Nevertheless in case of non-treated straw there are higher values of standard deviations. This result is caused by filling of digesters by non-homogenous straw which must have been cut to small pieces because of its length in relation to dimensions of digesters. The filled straw of different sizes caused the differences among the biogas production. If non cut straw could be used, the difference of biogas yield between non-treated/milled should be higher.

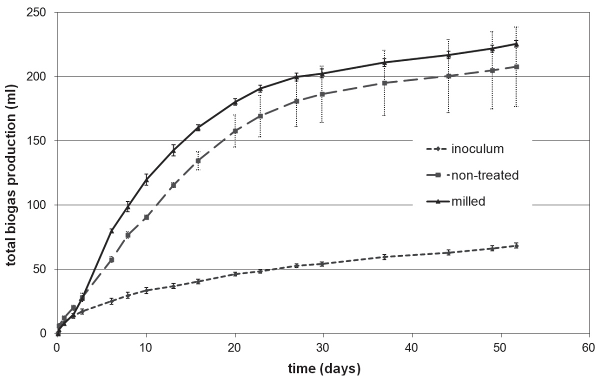

Fig. 3. The total biogas production (dry gas under standard conditions)

To evaluate specific biogas production, total substrate production was recalculated and related to the unit COD of added sample. The biodegradability was determined as the ratio of specific to theoretical biogas production, all based on the knowledge COD. All these results are summarized in Tab. 1. It is clear that the mechanical disintegration of wheat straw by macerator definitively increases biogas yield by 10% and its biodegradability also by 10%.

Tab. 1. The comparison of the specific biogas/methane production and biodegradability

Sample	Specific production		Biodegradability (%)
	Biogas (Nm^3·kg^{-1} COD)	Methane (Nm^3·kg^{-1} COD)	
non-treated	0,445	0,245	70
milled	0,491	0,278	79,5

Conclusions

The mechanical disintegration is an effective preliminary step at biogas plants resulting with the increase in biogas yield and in biodegradability of lignocellulosic biomass. The new type of disintegrator was developed in order to decrease energy demand related to final particle sizes, to increase biogas yield and to perform mechanical disintegration as a cost effective preliminary operation. Thus the test experiments of macerator confirmed these facts:

– The reached final particle size of wheat straw particles was lower than 10 mm.
– The energy demand to reduce straw in size from untreated state to final straw sizes lower than 10 mm was only 29 kWh·t^{-1}.
– The mechanical disintegration caused the increase in biogas yield was by 10% and in biodegradability by 10%.

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