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Experimental Identification of Specific Energy Demand for Knife Milling of Beech Chips at Different Moistures

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The paper scoped to identify specific energy demand of knife milled beech chips in dependence on moisture, initial and final particle size. The experiments were conducted for beech chips of moisture being 0.5, 7.5 and 16 % wt. dry mass, under mechanical size reduction in the knife mill with the fixed rotational speed of single blade rotor. The specific energy demand of 8.1 - 55.6 kWh t^{-1} was determined to reach final particle size 0.3 - 1.0 mm from initial 3.4, all as D_{50} value for given moistures. Regarding the brittle behaviour of beech chips, the Rittinger theory was applied, and the empiric model was defined to predict the energy requirement of size reduction relation to moisture and biomass particle size.

1. Introduction

Mechanical size reduction belongs among the crucial steps that significantly affects waste to biofuel or waste to biochemicals conversion rate and energy demand of a comprehensive waste conversion technology. The suitable particle size of 1 - 6 mm for pulverised waste co-firing technologies (Gil et al., 2012), 0.2 - 1.5 mm for gasification (Oyedi et al., 2020), or particles up to 3 mm for pyrolysis (Zamostny and Kurc, 2011) and gasification (Ruoppolo et al., 2011) in a fluidised bed were reported. Junling et al. (2011) present that the suitable waste particle size of its biochemical treatment should be kept in ranges 1 - 10 mm to reach effective biodegradability. This statement fits the recommendation given by Miao et al. (2011) that bioethanol production technology requires corn stover of 0.5 - 3.0 mm in size. Nevertheless, a high energy requirement is often needed to reduce particle size to the size needed for following treatments. It must be highlighted that the energy demand for size reduction could rise to 33 % of overall energy demand for given waste treatment technology (Mudhoo, 2012). Thus, the identification of energy demand for size reduction of biomass is an essential step that allows predicting the operating cost of a comprehensive waste treatment technology.
Generally known, the energy demand of mechanical size reduction depends on size reduction machine and its variables, on biomass characteristics (flowrate, chemical composition, moisture content), and demanded size reduction ratio, i.e. ration initial over final particle size (Kratky and Jirout, 2011). There is plenty of reports regarding the experimental evaluation of energy demand for mechanical size reduction of lignocellulosic biomass at one moisture by knife or hammer mills. E.g. Tumuluru et al. (2014) present energy demand 2.91 kWh t^{-1} for canola straw with 15.1 % wt. in moisture, 3.15 kWh t^{-1} for barley straw with 13.5 % wt. in moisture, and 8.05 kWh t^{-1} for oat straw with 13.1 % wt. in moisture. Cadoche and Lopéz (1989) experimentally identified energy demands 21 kWh t^{-1} and 42 kWh t^{-1} for hammer milled wheat straw with 4-7 % wt. in moisture from an initial size of 22.4 mm to final one being 3.2 and 1.6 mm. The energy requirements of 51.55, 39.59 and 10.77 kWh t^{-1} were reported by Yu et al. (2003) for hammer milled wheat straw, with 8.3 % wt. in moisture, from initial particle size, varied between 20 and 50 mm to 0.794, 1.588, and 3.175 mm. Bitra et al. (2009) determined specific energy demand of 7.57, 10.53, and 8.87 kWh t^{-1} for knife mill equipped by the screen size of 25.4 mm for corn stover, wheat straw, switchgrass, and wheat straw, all under 9 % wt. in moisture. Mani et al. (2009) published energy demand for a size reduction ratio 7.67/0.8 mm for wheat straw being 51.55 kWh t^{-1} with 8.3 % wt. in moisture, and 45.32 kWh t^{-1} with 12.1 % wt. in moisture. The authors also present energy demand for a size reduction ratio 12.48/0.8 mm for corn stover being 22.07 kWh t^{-1} with 6.2 % wt. in moisture, and 34.3 kWh t^{-1} with 12.0 % wt. in moisture. Eisenlauer and Teipel (2020) analysed energy demand for the knife- and

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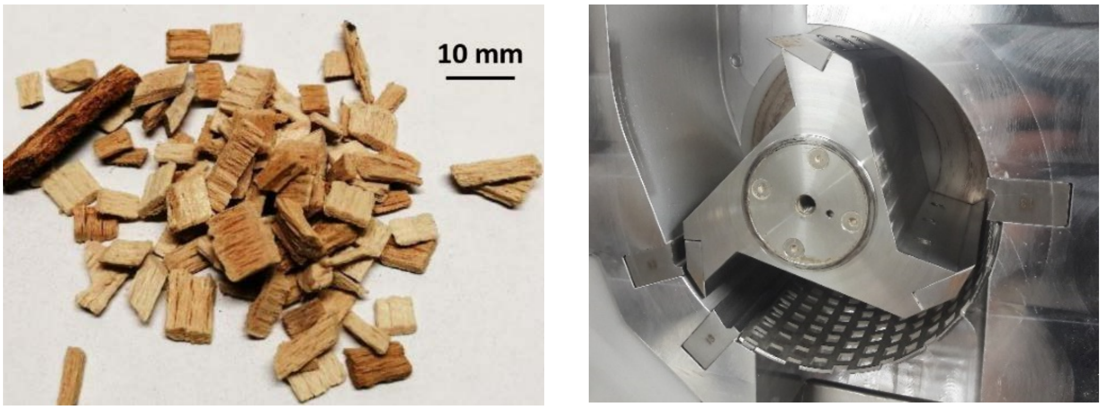
hammer-milled spruce and oak at different moistures being 1.5 % wt. and 34 % wt. Inspecting all the approaches of data evaluation, it was found that most of the papers offer only rough data for given experimental set-up with no application of modelling approach. If there is the effort to describe it, then on regression using linear, polynomic or power functions is often applied.
A little information is provided about the prediction of energy in dependence on machine variables and biomass characteristics, moisture especially. Thus, the paper aims to define a model predicting energy demand for knife milled beech chips of different moistures on machine variables.

2. Methods

The systematic experiments were done according to the following scheme, in which the dependences among particle size characteristics, size reduction ratio, and energy demand were studied concerning biomass moisture and knife mill variables.

2.1 Experimental set-up

Beech chips with moistures 0.50 ± 0.03 % wt. dry mass, 7.50 ± 0.01 % wt. dry mass, and 16.0 ± 0.1 % wt. dry mass was used to carry out the experiments. The solid organic content of 91.70 ± 0.03 % wt. dry mass was analysed for the given material. The totals solids were determined by drying of 5 representative samples in the dryer KBC-25W at the temperature of 105 °C up to constant weight. The solid organic content was determined by burning of 5 representative samples in the furnace LE09/11 at the temperature of 550 °C up to constant weight. The analytic balance SDC31 was used to determine the required masses. Raw beech chips see Figure 1a, were initially pre-grinded by the knife mill SM300 in configuration with a three-blade rotor, its revolutions of 3000 rpm, and the drum screen sieve with square openings of 10 mm in size.



a) The initial sample of wood chips. *b) The size reduction chamber of the mill SM300.*

Figure 1: The experimental set-up.

The dependences among particle size characteristics, size reduction ratio, and energy demand were experimentally identified for the mutual combinations of biomass moisture, fixed peripheral speed of the rotor, drum screen sieve size and inlet particle size distribution. The laboratory knife mill SM300 was used to carry out all the experiments. The three-blade rotor equipped with straight knife blades, see Figure 1b, was installed in the machine to reduce wood chips under the constant peripheral speed of revolution being 20.4 $m\ s^{-1}$ (3000 min^{-1}). The conventional screen sieves with square sized openings 6 mm (SC6), 4 mm (SC4), 2 mm (SC2), and trapezoidal sized openings 1 mm (SC1), and 0.75 mm (SC0.75) were used during the experiments.
The experiments were conducted according to the following scheme. The test sample of beech chips was characterised by its weight and particle size distribution. The triplicated experimental analysis of size reduction was always done for a given configuration of the knife mill. The feeding of the mill was done manually, keeping a constant active power and avoiding plugging of the size reduction chamber. Finally, the treated samples were weighted and analysed in particle size distribution.

2.2 Data analysis

The initial and milled samples were weighted by the precision balance Kern 573-46. The standard screen sieve certified by ASABE S424.1 "Method of Determining and Expressing particle size of chopped forage materials by screening", was used to determine the particle size distribution of initial and milled samples. Rosin-Rammler-Sperling-Bennet (RRSB) distribution was recommended by several reports (Eisenlauer and Teipel, 2020; Miao et al., 2011; Tumuluru et al., 2004) to regress cumulative mass fraction proportions of milled biomass. The analysed cumulative mass perceptual proportions were regressed using the RRSB distribution equation:

$$D_F = D_P \cdot [-ln(1-F)]^{\frac{1}{n}} \tag{1}$$

in which F (% wt.) is a cumulative mass fraction smaller than a given characteristic particle size D_F (mm), D_P (mm) means a characteristic particle size at the cumulative mass fraction 63.2 % wt., and n (-) expresses an index of polydispersity.

The experimental identification of energy demand for size reduction was based on the analysis of active power in a time, provided by the power analyser Fluke 438III. One experimental configuration of knife variables always had two runs. The first run recorded an active power during the milling of beech chips. The second one was idle, without any material, to evaluate all the passive resistances. The active power was simultaneously recorded with 0.5 s in time step. Finally, the specific energy requirement for size reduction of beech chips e (W s) under a given experimental configuration was calculated as:

$$e = \frac{\int_0^t P_{AM}\, dt - \int_0^t P_{AI}\, dt}{m} \tag{2}$$

where P_{AM} (W) is the active power during biomass milling at a given time t (s), P_{AI} (W) means the active power during the idle state at the same time t (s), and m (kg) expresses the weight of the treated sample.

3. Results and Discussion

Each experimental run of beech chips milling was characterised by mass flowrate given by the ratio between the weight of sample m processed at time t, energy demand e and particle size characteristics. The gained experimental results of screen sieve analysis were regressed by RRSB model, applying the least square method. The identified characteristic parameters of RRSB models for individual runs are presented in Table 1. Figure 2 plots the comparison of experimental data and regressed RSSB models. The points represent experimental data and lines show the regressed RRSB model of the cumulative mass particle size distribution. Knowing characteristics of D_P and n for defining particle size characteristics of the individual experimental run, D_{50} particle size at cumulative mass fraction 50 % wt. was evaluated as the base characteristic value of given particle size distribution.

Table 1: The particle size characteristics of knife-milled beech chips on the dependence on moisture x and individual runs given by screen sieves at constant peripheral rotor velocity of 20.4 m s^{-1}.

	characteristics of particle size for individual runs					
	initial	SC6	SC4	SC2	SC1	SC0.75
x = 0.5 % wt.						
D_P (mm)	4.24	0.97	0.82	0.48	0.40	0.37
n (-)	1.73	2.96	2.31	2.48	2.95	3.06
D_{50} (mm)	3.09	0.85	0.69	0.41	0.36	0.32
x = 7.5 % wt.						
D_P (mm)	4.24	1.00	0.80	0.64	0.55	0.47
n (-)	1.73	1.82	1.81	2.74	2.27	2.42
D_{50} (mm)	3.09	0.82	0.66	0.56	0.46	0.40
x = 16.0 % wt.						
D_P (mm)	4.24	1.39	0.89	0.66	0.42	0.36
n (-)	1.73	1.98	1.98	2.50	2.97	2.68
D_{50} (mm)	3.09	1.04	0.73	0.57	0.37	0.31

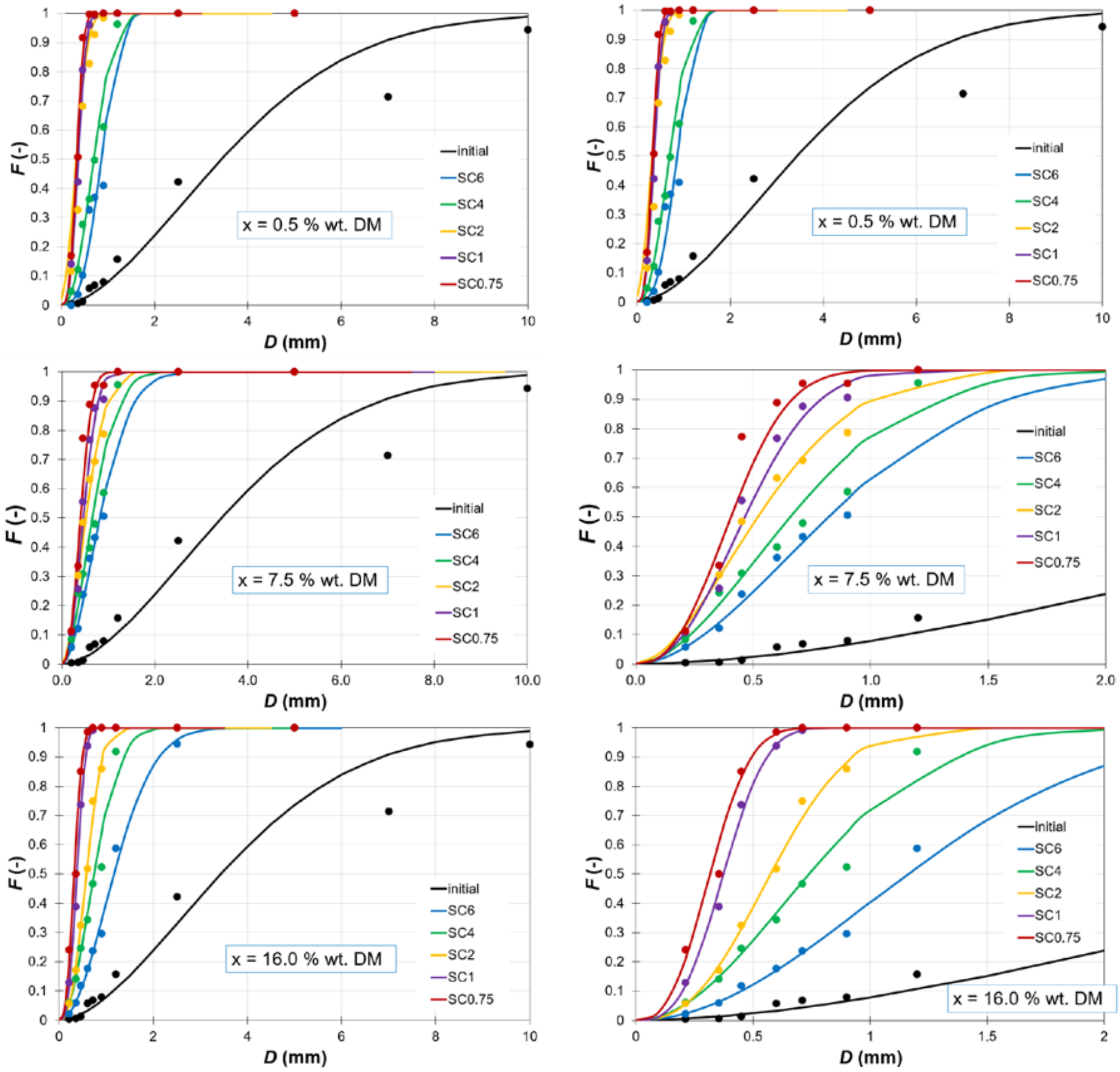


Figure 2: Dependence of particle size characteristics on screen size SC and moisture (point – experimental value, curve – fitted RRSB model).

The specific energy demand of 8.1 - 55.6 kWh t^{-1} was determined to reach final particle size 0.3 - 1.0 mm from initial 3.4, all related to D_{50} value for given moistures. The order of experimental values well fits specific energy demands reported for 2.91 kWh t^{-1} for canola straw with 15.1 % wt. in moisture (Tumuluru et al., 2014), 51.55 kWh t^{-1} for a wheat straw with 8.3 % wt. in moisture, and 45.32 kWh t^{-1} with 12.1 % wt. in moisture (Mani et al., 2009).

Generally known, Rittinger, Kick, Walker, Bond, Hucki or Morell comminution laws are typically used to predict energy demand of mechanical size reduction. Tumuluru et al. (2014), Miao et al. (2011) or Eisenlauer and Teipel (2020) found that biomass of low moistures evinces brittle behaviour. Then the Rittinger comminution law can be applied to model specific energy requirement e (kWh t^{-1}) for particle size reduction as:

$$e = C_{RD50} \cdot X_R \qquad (3)$$

$$X_R = \left(\frac{1}{D_{50}^{OUT}} - \frac{1}{D_{50}^{IN}}\right) \qquad (4)$$

where C_{RD50} (kWh mm^{-1} t^{-1}) is Rittinger constant, D_{50}^{IN} (mm) represents biomass particle size after milling, D_{50}^{OUT}(mm) biomass particle size before milling, all related to D_{50} value of particle size distribution.

The measured data of energy demand related to X_R parameter were regressed by Eq(4) for individual moistures, see Figure 3. Firstly, it is evident that the energy requirement is directly proportional to X_R parameter that confirms the assumption of brittle behaviour for beech chips. Secondly, it is also clear that the slope of individual linear regression functions, representing Rittinger constant C_R, is dependent on biomass moisture. Generally known, Rittinger law ignores deformation of particle before its fracture. Thus, energy demand is directly proportional to the increase in the surface that is generated by the shear of biomass particle between knives. Rittinger constant is inflicted by strength yield of beech chips that vary with moisture. It is evident that there is the leap between dry beech chips of 0.5% wt. in moisture and wet beech chips of 7.5 % wt. and 16.0 % wt. in moisture. Dry beech chips of 0.5% wt. in moisture are rigid and brittle. Thus, the shear is the dominant mechanism of mechanical size reduction. As the moisture of beech chips is increasing, its toughness is decreasing, and biomass becomes elastic. The mutual combination of shear and attrition is the mechanism of mechanical size reduction.

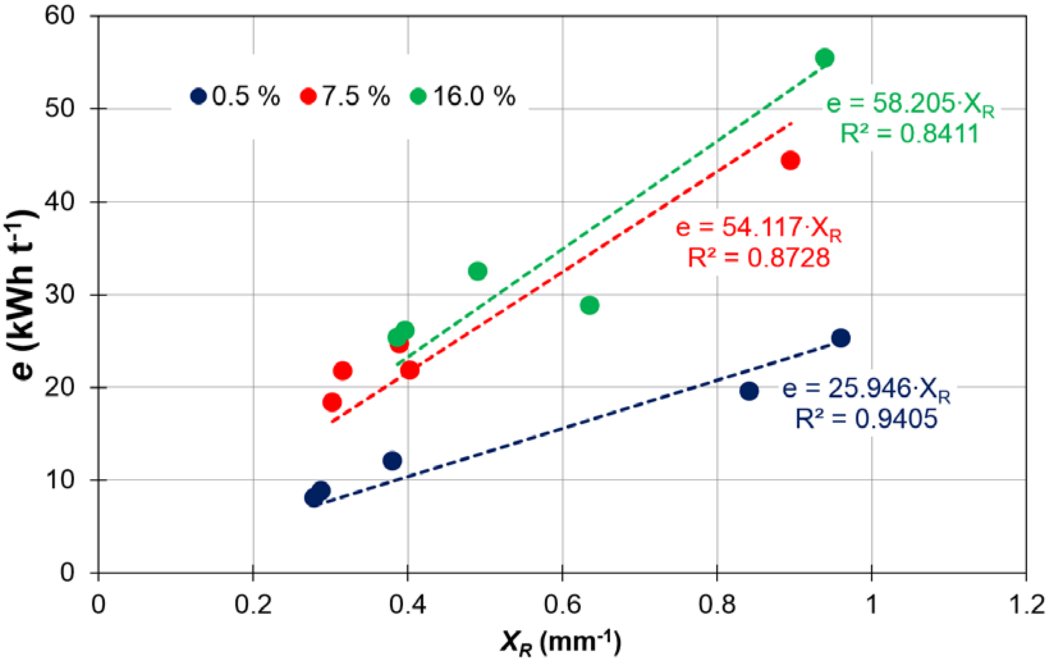


Figure 3: The dependence of specific energy demand e on X_R parameter and moisture x at peripheral rotor velocity 20.4 m s^{-1} (point = experimental data, line = fitted regression curve).

Table 2: The overview of results.

Parameter	Formula	Validity ranges	R^2 (-)
specific energy demand	$e = C_{RD50} \cdot \left(\frac{1}{D_{50}^{OUT}} - \frac{1}{D_{50}^{IN}} \right)$	Beech chips - total solids 84.0-99.5 % wt dry basis - moisture x = 0.5-16% wt. dry basis - volatile solid 92.2 % wt dry basis - input D_{50} size 0.36-3.09 mm - output D_{50} size 0.31-1.04 mm Knife mill - flowrate 25-128 kg h^{-1} related to the total length of installed knife blades - peripheral velocity 20.4 m s^{-1} - 0.75-6.00 mm screen sieve size Rittinger constant C_{RD50} related to D_{50}	
		- 25.9 kWh mm^{-1} t^{-1} for moisture 0.5 % wt.DM	0.94
		- 54.1 kWh mm^{-1} t^{-1} for moisture 7.5 % wt.DM	0.87
		- 58.2 kWh mm^{-1} t^{-1} for moisture 16.0 % wt.DM	0.84

The gained results indicate that the mechanism of size reduction is changing from shear to combined shear and attrition in dependence on biomass moisture. Dry beech chips evince Rittinger constant C_{RD50} of 25.9 kWh mm^{-1} t^{-1} wt dry mass related to D_{50} particle size. Moistured beech chips show Rittinger constants of 54.1 kWh mm^{-1} t^{-1} wt dry mass for the moisture of 7.5 % wt dry mass, and 58.2 kWh mm^{-1} t^{-1} wt dry mass for the moisture of 16.0 % wt dry mass. Based on these values, the model that allows predicting the specific energy requirement of mechanical size reduction concerning moisture and biomass particle size was defined with acceptable validity ranges, as presented in Table 2.

4. Conclusions

Beech chips of various moisture and size were reduced in size by the knife mill to define the model that allows predicting specific energy requirement of comminution. The specific energy demand of 8.1 - 55.6 kWh t^{-1} was identified to reach biomass particle size 0.3 - 1.0 mm in D_{50} under given experimental conditions. It was found that beech chips of moisture 0.5 - 16.0 % wt. dry mass evinces brittle behaviour. Dry beech chips of 0.5% wt. in moisture are rigid and brittle. The shear is the dominant mechanism of mechanical size reduction. As the moisture of beech chips is increasing, its toughness is decreasing, and biomass becomes more elastic. The mutual combination of shear and attrition is the mechanism of mechanical size reduction. The Rittinger comminution law was found to be an applicable model to predict the energy requirement of size reduction with Rittinger constant C_{RD50} equal to 25.9 - 58.2 kWh mm t^{-1} for D_{50} particle size in dependence on biomass moisture.

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