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The Effect of Moisture on Specific Energy Demand for Knife-milled Wheat Straw

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The paper analyzed the effect of moisture on specific energy requirements for knife milled wheat straw. The wheat straw with moistures of 3.1 wt %, 8.1 wt % and 22.9 wt % were comminuted under various rotors´ peripheral speeds and opening sizes, being at drum sieves of the knife mill with biomass flowrates 116.1-414.1 kg h^{-1} m^{-1} of the total length of installed blades in pair. The specific energy requirement of 0.28-40.12 kWh t^{-1} was identified to reach the final particle size D_{50} of 0.25-1.42 mm from the initial one of 2.67 mm. The Rittinger law precisely fits the experimentally determined values of specific energy requirements dependent on particle size characteristics and biomass moisture. The Rittinger constant was equal to 7.55-49.30 kWh mm t^{-1} for moisture ranges 3.1-22.9 wt % evincing its power-law dependence on biomass moisture.

1. Introduction

Mechanical size reduction is often the initial pretreatment step of thermochemical or biochemical lignocellulosic biorefineries. This is because size reduction of lignocellulosic biomass ensures an increase in specific particle surface causing an intensification of momentum, heat and mass transfer phenomena, improves pump-ability (Wiliams et al., 2017), handling and dosing of treated suspensions, or forming of particles into pellets (Pintana et al., 2020). Knife or hammer mills are usually used to reach final biomass particle sizes in the order of units in millimetres (Junling et al., 2011). Thus, mechanical energy input is needed to reduce particles from initial to a targeted particle size between mill working tools. Generally known, energy requirement depends on biomass properties (mechanical properties, chemical composition, moisture), on size reduction machine variables (biomass flow rate, type and geometrical set-up of working knife tools, peripheral speed of revolution, size and shape of openings in installed screen sieve), and on the particle size reduction ratio defined as a ratio initial over final characteristic particle size (Kratky and Jirout, 2011). Nevertheless, little information is served to define a dependence of energy requirement on biomass characteristics. The regressed power (Eisenlauer and Teipel, 2020), exponential (Gil et al. (2012), polynomic (Mani et al., 2004) or linear (Eisenlauer and Teipel, 2021) functions were used to model specific energy demand for hammer-milled biomass. Nevertheless, the theory offers Bond, Rittinger, or Kick comminution laws to model specific energy requirements dependent on material behaviour, particle size characteristics and size reduction principle. E.g., Liu et al. (2020) found that Bond law fitted to model specific energy for hammer-milled douglas-fir residues at different moistures. Srikanth Tangirala et al. (2014) identified the suitability of Bond law to quantify the relationship between specific energy and particle size for hammer milled spice powder. Temmerman et al. (2013) applied the Rittinger law to model specific energy requirements on particle size for hammer milled wood chips at five different moistures. Ghorbani et al. (2010) identified the Rittinger law to model specific energy demand hammer-milled alfalfa. However, most studies apply hammer mill and crushing as the dominant size reduction principle.

Regarding the novelty, the paper deals to experimentally analyse the dependence of specific energy demand on wheat straw characteristics at different moisture comminuted by knife mill that applies the shear principle of size reduction. The application potential of conventional modelling approaches was statistically tested, based on which a model allowing to predict energy requirement of size reduction on process variables was defined.

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2. Materials and Methods

The experimental works were carried out regarding the following scheme.

2.1 Raw material

The wheat straw was used in the experiments. The knife mill initially reduced the raw wheat straw to reach uniform particle size distribution. The knife mill SM300 was equipped with a screen sieve of 10 mm in a square opening, the three-bladed rotor was installed and run with the peripheral velocity of 3000 rpm. Pre-milled wheat straw was analyzed in total and volatile solids. The natural wheat straw evinces moisture 3.10 ± 0.03 wt % dry mass and volatile solids of 94.80 ± 0.10 wt % dry mass. The moistures were determined by drying three representative samples in the dryer KBC-25W under the temperature of 105 °C up to constant weight. The volatile solids were determined by burning three representative samples in the furnace LE09/11 at 550 °C up to constant weight. The effect of wheat straw moisture on specific energy requirements was studied for the moistures of 3.1, 8.1 and 22.9 wt %. The samples with moisture over the native one were reached by spraying a proper amount of water to the whole particle surface. Wetted samples were closed into gas-tight sacks and kept three weeks in a refrigerator at a temperature of 4°C to reach the uniform moisture content in all the particles. Before the experiments, the moistures of 8.10 ± 0.38 wt % dry mass and 22.90 ± 0.51 wt % were analyzed.

2.2 Knife mill

The laboratory knife mill SM300 was used to conduct all the experiments see Figure 1a. Its size reduction chamber was equipped with a three-bladed rotor with a single sharp length of 95 mm, as shown in Figure 1b. The experimental plan was based on the mutual combinations of wheat straw moisture (3.1 wt %, 8.1 wt %, 22.9 wt %), two peripheral speeds of rotor revolution being 10.2 m s^{-1} (1500 min^{-1}) and 20.4 m s^{-1} (3000 min^{-1}), and on the variable size reduction ratio influenced by the installation of screen sieve into size reduction zone of the mill. The screen sieves of square openings with the sizes of 10 mm, 6 mm, 4 mm, 2 mm, and trapezoidal ones of sizes 1 mm, and 0.75 mm were used.

a) The laboratory knife mill SM300.

b) The size reduction zone with wheat straw.

Figure 1: The experimental machine.

2.3 Experimental set-up

The experimental analysis of specific energy requirements for individual experimental runs was carried out according to the following scheme. The straw sample was firstly weighted and analyzed in particle size distribution. Then, the sample milling followed under the given process variables of the experimental plan. Finally, the milled sample was weighted and analyzed in particle size distribution.

The standard screen sieve analysis did particle size analysis according to the ASABE standard S424.1 (2017) that defines the exact methodology to evaluate particle size characteristics for biomass. First, the particle size distribution was recognized for each treated sample using Rosin-Rammler-Sperling-Bennet (RRSB). Then, its typical parameters, known as the polydispersity index and characteristic particle size at the cumulative mass fraction 63.2 wt %, were identified. So each experimental run was characterized by characteristic particle diameters D_{50} (mm). The symbol D_{50} represent particle size at a cumulative mass fraction of 50 wt %.

Measures of active power evaluated the specific energy demand by power analyzer Fluke 438III in time-related to reducing in size a given amount of sample. Each experimental run had two phases, i.e. idle and active. The energy requirement in the idle state represented the situation during which no material is processed in the size reduction zone. Thus, the resulting measured energy covers only all the passive resistances of the mill at set working conditions. The active state and its related energy demand correspond to the energy needed to reduce a given amount of sample in a given time. The specific energy demand was determined according to the formula.

$$e \quad = \frac{1}{m} \cdot \left(\int_0^t P_{AM}\, dt - \int_0^t P_{AI}\, dt \right) \tag{1}$$

The symbol P_{AM} (W) is the active power size reduction of a sample in a given time t (s), P_{AI} (W) is the active power analyzed for the idle state at the same time, and m (kg) is the weight of the treated sample. The active power was analyzed and stored with a period of 1 s.

3. Results and Discussion

The mass flowrate of wheat straw, specific energy demand, particle size distribution characteristics for the RRSB model, and D_{50} value were evaluated for each configuration of the experimental plan. The specific energy demand of 0.28-40.12 kWh t^{-1} was determined to reach the final particle size D_{50} of 0.25-1.42 mm from the initial one of 2.67 mm. The presented experimentally achieved specific energy requirements are close to the values of some reports evaluating energy demand for milled biomass. E.g. Tumuluru et al. (2014) reported a specific energy requirement of 2.91 kWh t^{-1} for canola straw with 15.1 wt % in moisture. Mani et al. (2004) presented a particular energy requirement of 51.55 kWh t^{-1} for a wheat straw with the moisture of 8.3 wt %. Yu et al. (2003) found specific energy requirements 10.77-51.55 kWh t^{-1} for a wheat straw with the moisture of 8.3 wt %.

As discussed in the introduction, there are conventional models, known as Kick, Bond, or Rittinger, comminution laws. All these models are based on the assumption that specific energy requirement e (kWh t^{-1}) needed for size reduction of a particle is inversely proportional to particle size D (mm) powered to the parameter r (-), see Eq. 2. The symbol C represents a general integration constant.

$$\frac{de}{dD} = -\mathrm{C} \cdot D^{-r} \tag{2}$$

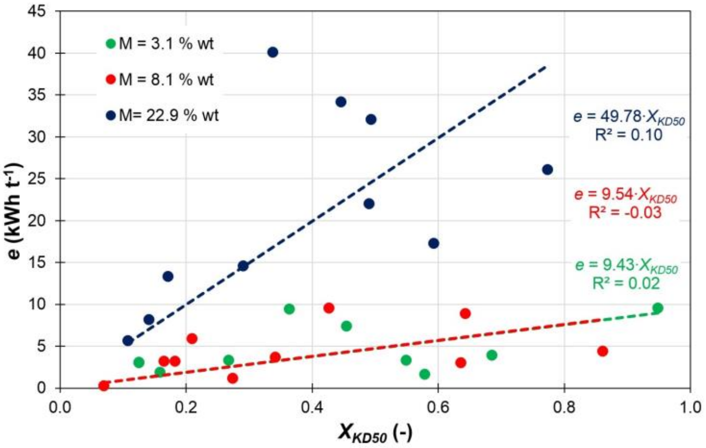

Figure 2: Modelling energy demand on particle size characteristic D_{50} and moisture M by Kick theory.

The Kick theory assumes energy needs to ensure a particle's elastic deformation followed by its crack. The r parameter is equal to 1 for this theory. Substituting general particle size D with particle size characteristic D_{50}, Eq. 2 with implemented r = 1 results in the Kick empirical model characterised by Eq. 3. The specific energy demand is directly proportional to the size reduction ratio, i.e., the input particle size D_{50IN} divided by output one D_{50OUT}. The symbol C_{KD50} (kWh t^{-1}) is the Kick constant of the model, and X_K (-) is a characteristic parameter of the Kick model.

$$e = C_{KD50} \cdot ln \frac{D_{50IN}}{D_{50OUT}} = C_{KD50} \cdot X_{KD50} \tag{3}$$

Eq. 3 was regressed to an experimentally identified specific energy requirements dependent on X_K parameter and individual moistures M (wt %). The results are presented in Figure 2. The CK value model slope increases with an increase in wheat straw moisture. This is because straw particles become more elastic with rising water content, i.e. a higher compression rate is demanded before its crack, increasing specific energy requirements. Nevertheless, the Kick theory is not applicable regarding the values of all the coefficients of determination.

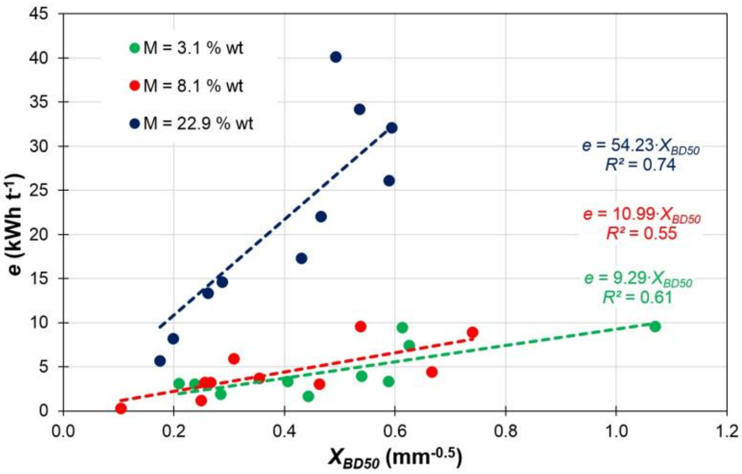

Figure 3: Modelling energy demand on particle size characteristic D_{50} and moisture M by Bond theory.

The Bond theory supposes that the energy needed for crack propagation is proportional to the new crack length. The *r* parameter is equal to 1.5 for this theory. Replacing general particle size *D* by particle size characteristics D_{50}, Eq. 2 with implemented *r* = 1.5 results in the Bond empirical model expressed by the model equation as presented by Eq. 4.

$$e = 2 \cdot C_{BD50} \cdot \left(\frac{1}{\sqrt{D_{50OUT}}} - \frac{1}{\sqrt{D_{50IN}}}\right) = C_{BD50} \cdot X_{BD50} \tag{4}$$

The symbol C_{BD50} (kWh mm$^{0.5}$ t^{-1}) represents the Bond model's constant and X_{BD50} (mm$^{-0.5}$) characteristic parameter of the Bond model. Eq. 4 was fitted to an experimentally identified specific energy demand concerning calculated X_{BD50} parameters and individual moistures *M*. The results are plotted at Figure 3. Regarding the values of all the coefficients of determination, it is evident that the regressed linear trend fits experimental data with a rough precision. Furthermore, the assumption of the elastic deformation followed by crack or generation of the new surface for wheat straw particles is applicable to the model energy requirement. Finally, the potential of applicability for the Rittinger comminution law was tested. This theory assumes that the energy required for size reduction is directly proportional to the particle surface increase. The r parameter is equal to 2 for this theory. Replacing general particle size *D* with particle size characteristics D_{50}, the integration of Eq. 2 with implemented r = 2 results in the Rittinger empirical model expressed by model equation Eq. 5.

$$e = C_{RD50} \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right) = C_{RD50} \cdot X_{RD50} \tag{5}$$

The symbol C_{RD50} (kWh mm t^{-1}) is the Rittinger constant of the model and the X_{RD50} (mm^{-1}) characteristic parameter of the Bond model. Eq. 5 was fitted to an experimentally identified specific energy demands concerning X_{RD50} parameter and individual straw moistures *M*. The results are plotted at Figure 4. The Rittinger model fits the experimental data with higher accuracy than the Bond model given by Eq. 4. Thus, the Rittinger comminution law is a suitable model that predicts specific energy demand on characteristic particle size and straw moisture. The identical conclusion about the applicability of the Rittinger comminution laws was stated by Temmerman et al. (2013) for knife-milled wood chips at different moisture or by Ghorbani et al. (2010) for hammer-milled alfalfa. Concentrating on the presented regression curves in Figure 4, it is clear that the slope of the model given by C_{RD50} value increases with an increase in wheat straw moisture *M*. Individual C_{RD50} values in dependence on moisture *M* were regressed to quantify the mutual relationship. Using the least square method for regression curves, it was found that the Rittinger constant C_{RD50} is power law dependent on the moisture *M* of wheat straw, see Figure 5. Applying the analogy, the strength yield of metallic materials goes down by power with increasing temperature, strength yield of biomass falls by power with increasing moisture. The Rittinger law ignores the deformation of a particle before its fracture. Thus, the energy demand is dependent only on the principle of size reduction. If biomass is dry, only shear reduces particles in size. On the other hand, if biomass moisture is increasing, biomass particles become elastic. The mutual effect of shear and attrition is responsible for the size reduction of particles between knives. Thus, higher energy demand is required for such a combination of size reduction principles to increase particle surface due to dependence on biomass moisture.

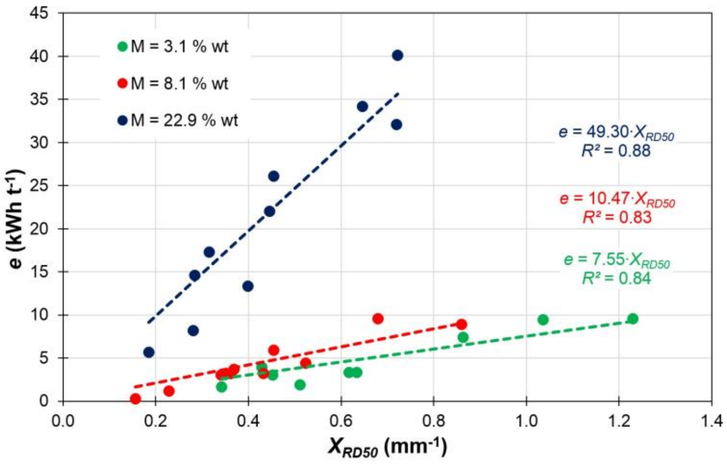

Figure 4: Modelling energy demand e on particle size characteristic D_{50} and moisture M by Rittinger theory.

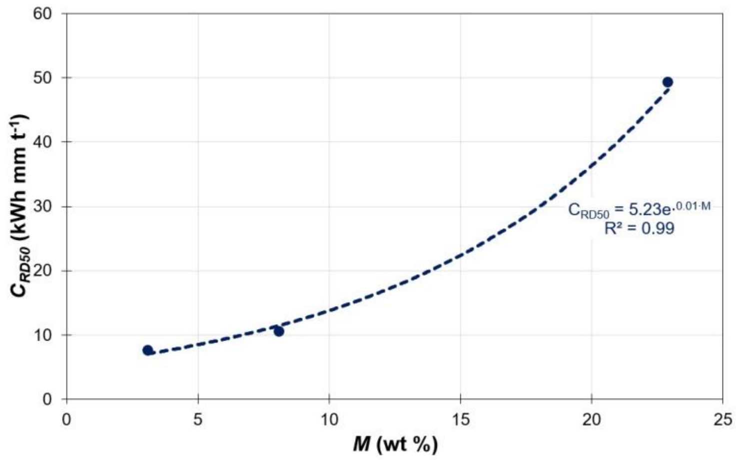

Figure 5: The dependence of Rittinger constant CR on particle size characteristics D_{50} and D_{90}.

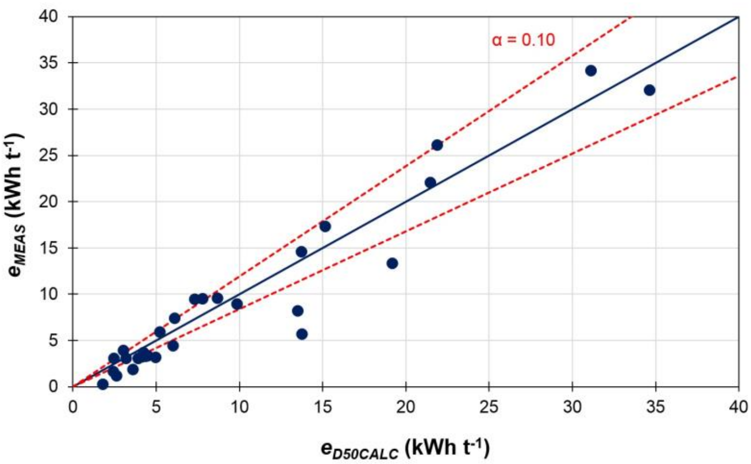

Figure 6: The prediction model of energy demand for knife milling of wheat straw with the confidence belts.

The results indicated that the empirical Rittinger comminution law fits to model the specific energy demand of wheat straw comminution in the knife mill. Its constant is power-law dependent proportional to biomass moisture. Based on all these findings, the prediction model was defined as presented in Eq. 6. The model serves the precision expressed by the confidence intervals in the confidence level of α = 0.10, see Figure 6. The e_{MEAS} (kWh t^{-1}) is measured, and $e_{D50CALC}$ (kWh t^{-1}) is calculated energy demand by Eq.6. Its application is limited to wheat straw with the moisture of 3.1-22.1 wt %, initial particle size D_{50IN} of 0.29-2.61 mm, final particle size D_{50OUT} of 0.25 – 1.41 mm, and size reduction in knife mill with biomass flowrates 116.1-414.1 kg h^{-1} m^{-1} related to the total length of knife blades in pair and peripheral rotor velocities 10.2-20.4 m s^{-1}.

$$e_{D50} = 5.23 \cdot e^{0.01 \cdot M} \cdot \left(\frac{1}{D_{50\mathrm{OUT}}} - \frac{1}{D_{50\mathrm{IN}}} \right) \quad (6)$$

4. Conclusions

The paper experimentally quantified the effect of moisture on specific energy demand for knife milled wheat straw. The specific energy requirement ranges were in units or lower tents of kWh t^{-1}. Conventional empiric approaches of Kick, Bond and Rittinger were tested to describe mutual relationships among specific energy demand, particle size characteristics and biomass moisture. The Rittinger comminution law showed the highest precision in modelling. The value of the Rittinger constant was power law dependent on moisture content.

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