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The Effect of Moisture on the Particle Size Characteristics of Knife-milled Beech Chips

Lukas Kratky*, Tomas Jirout, Martin Dostal, Mehmet Ayas

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Process Engineering, Technicka 4, 160 00, Prague 6, Czech Republic
Lukas.Kratky@fs.cvut.cz

The paper presents the effect of moisture on the particle size distribution of knife-milled beech chips. The beech chips of 0.5, 7.5, 15.9 and 30.9 wt % in moisture were milled by a knife mill equipped with a single-bladed rotor under the constant peripheral speed of revolution of 10.2 $m \cdot s^{-1}$ (1,500 min^{-1}). It was found that the RRSB model precisely fits cumulative mass particle size distribution. The Rosin–Rammler size parameter 0.412 - 4.240 mm varies concerning biomass moisture and size of drum screen sieve. Assuming empiric modelling approaches, it was found that the Rosin–Rammler particle size exponentially decreases with a decrease in knife mill screen sizes and linearly increases with biomass moisture. The polydispersity index was independent of wood chips moisture and knife mill screen size, evincing the value of 2.224 ± 0.328.

1. Introduction

Biomass particle size belongs among the crucial operating parameters that significantly affect biomass conversion efficiency via several technological pathways like briquetting, pelleting, gasification, pyrolysis, hydrolysis, or fermentation into targeted products. Gil et al. (2012) published the targeted biomass particle sizes 1-6 mm fo biomass co-firing, 3 - 5 mm for pelleting, and 5-10 mm for briquetting. Bitra et al. (2011) recommended biomass particles of 0.03 - 10 mm for efficient fermentation. Ruopollo et al. (2011) present particle sizes 0.12-10.00 mm for fluidized bed gasification of lignocellulosic biomass. Knife or hammer mills are typical size reduction machines that are usually used to reduce particles to demanded size being typically in the order of millimetres. Particle size distribution is affected by biomass characteristics (moisture, chemical composition, mechanical properties) and mill variables (biomass flowrate, rotor type, peripheral speed of revolution, screen sieve size).

Nevertheless, little information is published regarding the relationships among mill variables, biomass moisture and particle size distribution of milled biomass. The list of a single value for characteristic particle sizes in dependence on screen sieve size is presented by Eisenlauer and Teipel (2020) for beech, oak and spruce at moistures of 1.5 wt % and 34 wt % without modelling approaches. Gil et al. (2012) also report only a tabled data overview of particle size characteristics for hammer-milled Cynara biomass. Lisowski et al. (2018) serve the tabular overview of the regression coefficient for the RRSB model describing the effect of screen sieve size on particle size characteristics of milled straw and hay biomass. Su and You (2019) regressed the relationship between characteristic particle size and screen size by power functions at one moisture. Kratky and Jirout (2020) found pure empirical power-law dependence of characteristic particle size on knife mill screen for the wheat straw of constant moisture in a given experimental range. Mani et al. (2004) present perceptual mass particle size distribution at nominal sieve sizes for hammer-milled wheat and barley straws at different screen sizes modelled as polynomic functions. The parabolic dependences between geometric mean length or parameters of RRSB particle size distribution model on screen sieve size are presented for knife milled corn stover (Bitra et al., 2009a), switchgrass (Bitra et al., 2009b), and wheat straw (Bitra et al., 2011), all with the moisture of 9 wt %. The parabolic relationship between geometric mean length and screen sizes was reported for knife milled miscanthus by Miao et al. (2011). Gil et al. (2014) applied neural networks to model relationships among geometric mean diameter for hammer-milled poplar and corn stover at different biomass moistures, process target diameter and angular speed of hammer mill rotor.

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A tiny piece of information is provided regarding the effect of moisture on the particle size distribution. The paper deals to experimentally identify and define a model that predicts the mutual relationship among particle size characteristics, wood chips moisture, and knife mill screen size at constant rotor speed.

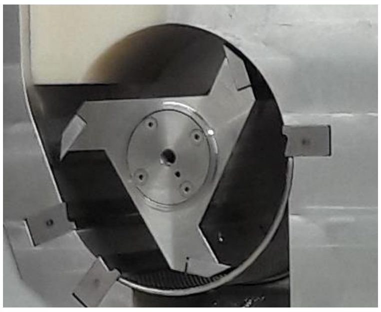
2. Materials and methods

All the experimental studies and modelling approaches were made applying such a methodology.

2.1 Materials

The raw beech chips see Figure 1a, were used in this study. The chips of native moisture were firstly pre-milled using the knife mill SM300 in configuration with a three-blade rotor with 1,500 rpm in angular speed of revolution, and the screen sieve with square openings of 10 mm in size, see Figure 1b. Then, the biomass samples were moistured by spraying proper water amount in gas-tight bags and stored for three weeks to reach homogeneous moisture across the particle. The beech chips of moistures 0.50 ± 0.03 wt %, 7.50 ± 0.01 wt % (native moisture), 15.90 ± 0.08 wt %, and 30.90 ± 0.54 wt %, all percentages related to dry mass, were used to carry out all the experiments, see Figure 1a. The solid organic content equal to 91.70 ± 0.03 wt % was identified for the given material. The totals solids were analyzed by drying five samples in the dryer KBC-25W at 105 °C up to constant weight. The solid organic content was identified by burning five samples in the furnace LE09/11 at 550 °C up to constant weight. The analytic mass balance SDC31 was used to get the masses of individual samples.

a) The initial sample of wood chips.



b) The size reduction chamber of the mill SM300.

Figure 1: The experimental setup.

2.2 Experimental layout

The relationship among the biomass moisture *M* (wt %), knife mill's screen sieve sizes *SC* (mm) and particle size characteristics were experimentally identified at the fixed angular velocity of the rotor of the knife mill SM300. The mill was equipped with a three-bladed rotor; its revolutions were kept at 10.2 $m \cdot s^{-1}$ (1,500 min^{-1}). The set of knife mill's screen sieves was used during the experiments with openings of 6 mm (SC6), 4 mm (SC4), 2 mm (SC2) in square size, and 1 mm (SC1), and 0.75 mm (SC0.75) trapezoidal ones. All the experiments were realized according to the following procedure. First, the sample before milling was weighted and analyzed in particle size distribution. Then, its mechanical size reduction followed according to a given configuration. Finally, the sample after milling was weighted and analyzed in particle size distribution.

2.3 Data analysis

The standard screen sieve analysis certified by ASAE S424.1 (2017) was applied to identify the particle size distribution of samples before and after milling. The accurate modelling approached was reported by Bitra et al. (2011) for switchgrass, Miao et al. (2011) for energy cane, miscanthus and switchgrass, or by Eisenlauer and Teipel (2020) for wood. The analyzed cumulative mass perceptual proportions were regressed by the RRSB model defined as:

$$F = 1 - e^{\left(-\frac{D_F}{D_P}\right)^n} \qquad (1)$$

in which *F* (wt %) means a cumulative mass fraction lower than a given characteristic particle size D_F (mm), Rosin–Rammler size parameter D_P (mm) represents a characteristic particle size at the cumulative mass fraction 63.2 wt %, and Rosin–Rammler distribution parameter *n* (-) expresses an index of polydispersity.

3. Results and discussion

Particle size characteristics described the systematic experimental runs under a given process configuration. The biomass flowrate 43-128 kg·h^{-1}·m^{-1} related to active length for pair of knives was regarded. The perceptual cumulative mass fraction of the given sample was regressed by the RRSB model, and its parameters D_P and n were identified. Figure 2 compares experimental data and fitted RRSB model at given moistures M.

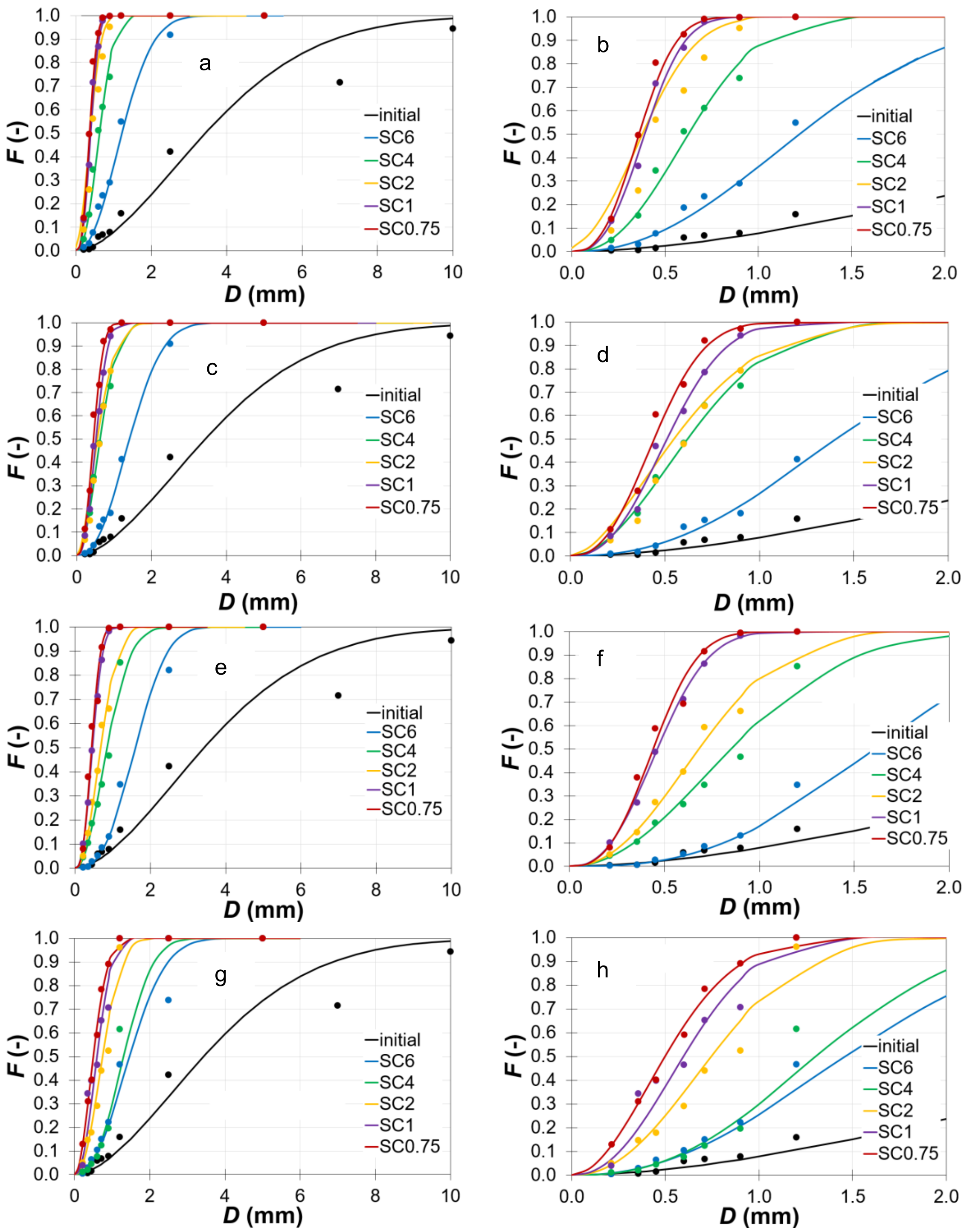


Figure 2: Dependence of particle size characteristics on screen size SC and moisture M at a constant peripheral rotor speed of 10.2 m s^{-1} (point – experimental value, curve – fitted RRSB model). a,b - 0.5 wt %, c,d - 7.5 wt %, e,f - 15.9 wt %, g,h - 30.9 wt %.

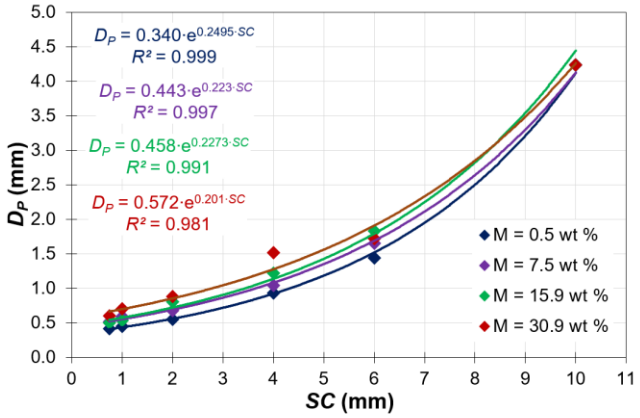


Figure 3: Dependence of D_P parameter on screen size SC and moisture M (point – experimental value, point – experimental value, line – regressed curve, SC10 – all the moistures fall into one point).

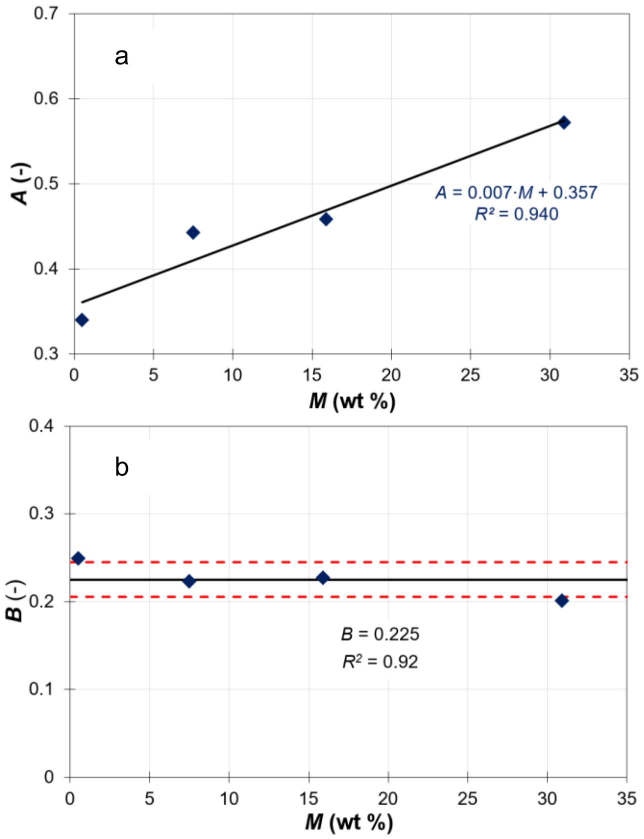


Figure 4: Characteristics parameters of Eq(2) related to moisture M (point – experimental value, line – regressed curve), a- A parameter, b - B parameter.

The effect of screen sieve size *SC* and biomass moisture *M* on Rosin–Rammler particle size D_P and index of polydispersity *n*. D_P and *n* characterize the particle size distribution of biomass samples before size reductio*n*. Supposing the brittle behaviour, biomass sample goes through size reduction zone, and it is cut between pair of static and rotating knives of a given active cutting length. If one particle goes one time through the size reduction zone, one cut generates two particles. Two cuts of one particle generate a maximum of four particles. The maximum of eight particles is generated by three cuts of one particle, etc. It means that the quantity of generated particles is exponentially dependent on a number of horizontal, vertical and diagonal particle cuts. The lower the screen sieve size, the higher the particles, the finer particle size distribution, the lower Rosin–Rammler particle size D_P. This finding fit other reports, in which the polynomic decrease of biomass particles on knife screen sieve was observed for wheat straw (Bitra et al., 2009a), poplar and corn stover (Gil et al., 2014), or switchgrass (Mani et al., 2004). Based on this hypothesis, it was supposed that mutual relationship between Rosin–Rammler particle size D_P and screen sieve size *SC* could be expressed as

$$D_P = \mathrm{A} \cdot e^{\mathrm{B} \cdot SC} \tag{2}$$

in which *A (-)* and *B* (-) are dimensionless characteristics of a given model. The least-square method was applied to fit Eq(2) to the dependence of experimentally identified Rosin–Rammler particle size D_P and screen sieve size *SC*, see Figure 3. It is evident that the model precisely fits the data. The coefficient of determination R^2 (-) is closed to one for all the regressed curves. The effect of moisture *M* on Rosin–Rammler particle size D_P was also studied. Regarding Figure 3, it is evident that the higher moisture *M*, the larger D_P particle size. Such behaviour is associated with the mechanical properties of biomass and size reduction principles. If biomass is dry, the only shear is generated between knives to reduce particles in size. As biomass moisture increases, biomass becomes elastic. The mutual effect of shear and attrition reduce particles in size between pairs of knives. The attrition of particles between pairs of knives primarily results in biomass defibering generating needle shape particles. As biomass moisture increases, the effect of attrition rises. This results in higher particle size distribution compared to brittle biomass. Thus, D_P particle size goes up with increasing biomass moisture *M*. The effect of biomass moisture *M* on *A* and *B* parameters was studied. It was found that *A* parameter is directly proportional to biomass moisture, see Figure 4a. The mechanical properties typically evince power-law dependence between shear strength and moisture. Such a general function can be linearized in a given range. The higher moisture, the lower the shear strength, the rise of attrition, the higher particle size resulting in a larger D_P particle size. It was found that the *B* parameter is independent of biomass moisture *M*. Its statistically gained value is equal to B = 0.225 ± 0.019. This value was reached using linear regression concerning the least square method followed by confidence intervals at the 0.05 confidence level. The coefficient of the determination is R^2 = 0.92, as plotted in Figure 4b.

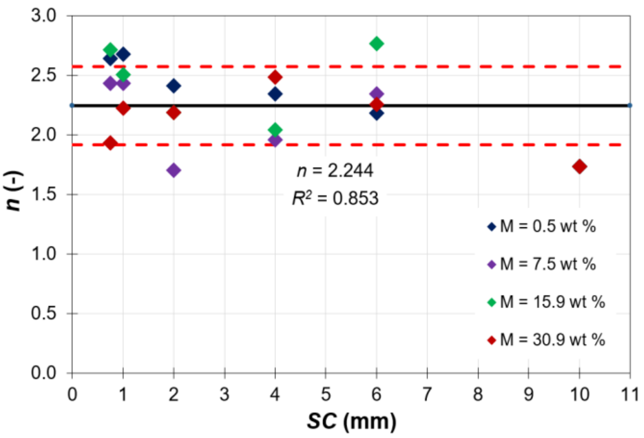


Figure 5: Dependence of n parameter on screen size SC and moisture M (point – experimental value, full curve – regression model, dash-dote curve – confidence band α = 0.05).

The dependence between the index of polydispersity *n*, screen sieve size *SC* and biomass moisture *M* was studied. Its value characterizes the heterogeneity of a given sample. Its values close to zero tend to be monodispersive. Its increasing values mean changes to the broad size distribution of particles. It was found that the index of polydispersity *n* (-) is independent of the characteristic screen size *SC* and biomass moisture *M*. Its statistically gained value is equal to n = 2.224 ± 0.328. This value was reached using linear regression concerning the least square method followed by confidence intervals at the 0.05 confidence level. Thus, the coefficient of the determination is R^2 = 0.853, as plotted in Figure 5.

$$D_{50} = \mathrm{D}_P \cdot e^{-\frac{0.366513}{n}} \tag{3}$$

$$D_{50} = (0.007 \cdot M + 0.357) \cdot e^{0.225 \cdot SC - 0.165} \tag{4}$$

The RRSB particle size distribution parameters D_P and *n* in dependence on moisture *M* and knife mill screen size *SC* can be modelled formulas and values discussed above. Nevertheless, the representative particle size of the sample after milling is usually served as the D_{50} particle size, i.e. particle size at the cumulative mass fraction of 50 wt %. Re-expressing Eq(1) and substituting F = 0.5, $D_F = D_{50}$, the D_{50} value can be calculated by Eq(3). Substituting D_P and n parameters by the identified models, the mutual relationship among characteristic particle size D_{50}, wood chips moisture M, and knife mill screen size SC can be modelled as presented by Eq(4). This prediction model is valid only for wood chips moisture 0.5 - 30.9 wt %, peripheral rotor speed 10.2 $m \cdot s^{-1}$, knife mill screen sizes 0.75 - 10.00 mm and biomass flowrate 43 - 128 $kg \cdot h^{-1} \cdot m^{-1}$ related to active length for pair of knives. The model serves the precision expressed by the coefficient of determination of R^2 = 0.731.

4. Conclusions

The original experimental works were carried out to identify the effect of beech chips moisture and knife mill screen size on particle characteristics under constant the constant peripheral speed of revolution. It was found that the RRSB model precisely fits cumulative mass particle size distribution. A deeper analysis of Rosin–Rammler particle size and polydispersity index were studied concerning wood chip moisture and knife mill screen size variations. The regression modelling and statistical analysis confirmed the theoretically assumed exponential dependence between characteristic particle size and knife screen sieve. The higher wood chips moisture and the knife mill screen size, the larger the size was reached after size reduction. The Rosin–Rammler particle size of 0.412 - 4.240 mm exponentially decreased with a decrease in screen sizes and linearly increases with moisture content due to the changes in biomass strength, rigidity, and changing proportions between applied size reduction principles (shear, attrition). Rosin–Rammler distribution parameter, index of polydispersity of 2.224 ± 0.328, was independent of wood chips moisture and knife mill screen size. The general empiric model was finally derived to simply predict the characteristic particle size D_{50} knowing only biomass moisture and screen sieve size in given experimental ranges.

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