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Mechanical Size Reduction Of Lignocellulosic Biomass: A Mini-Review

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The principles of biomass mechanical size reduction and models predicting specific energy requirements of biomass comminution on particle size characteristics and machine variables were summarized in this mini-review. It was identified that lignocellulosic biomass up to 25 wt % in moisture is usually mechanically reduced in size by cutting, shearing, tearing, or breaking, primarily provided by knife or hammer mill. The specific energy requirement of these size reduction machines depends on targeted size reduction ratio (initial over final characteristic particle size), on biomass properties (chemical composition, mechanical properties, moisture), and mill variables (geometrical set-up of working tools, rotor revolutions, drum screen sieve size). Specific energy demand for mechanical biomass size reduction usually ranges in units or low decimals of kWh t^{-1}. Rittinger's comminution law was found to precisely predict a model determining specific energy requirements related to change in particle size characteristics of a hammer- or knife-milled biomass. Rittinger's constant varies with biomass properties and machine variables.

1. Introduction

Mechanical size reduction is recognized as the crucial pretreatment step for lignocellulosic biorefineries. It is known that the mechanical size reduction process of lignocellulosic biomass modifies the particle size and shape, brings its easy handling and drying or reduces the cost of transportation (Miu et al., 2006). It ensures an increase of specific surface, increases bulk density, causes shearing or defibering of biomass particles, and reduces polycrystalinity (Lisowski et al., 2018). Hendriks and Zeeman (2009) highlighted that milling increases subsequent hydrolysis yield by 5 - 25 % and reduces the digestion time by 23 -5 9 %. All the lignocellulosic waste treatment technologies, i.e. thermal (combustion), thermochemical (gasification, pyrolysis) and biochemical (biogas or bioethanol production technologies, hydrolysis processes), demand biomass particle size in units or lower tens of millimetres to reach a suitable process efficiency reducing environmental waste footprint.

E.g. Hoque et al. (2007) present particle sizes less than 6 mm for pelleting and briquetting or under 1 mm for pulverized biomass burners due to similar residence times like pulverized coal. Biomass particle sizes of 0.25 - 2 mm for pyrolysis and 0.2 - 1.5 mm for gasification are recommended by Oyedeji et al. (2020). Ruopollo et al. (2011) recommend biomass particle sizes of 0.12 -10.00 mm for fluidized bed gasification. The biomass particle size of 0.03-10 mm is essential for fermentation (Oyedeji et al., 2020). Miao et al. (2011) present the need for 0.5-3.0 mm in corn stover for bioethanol production technology. Mechanical size reduction is also viewed as a very high energy-demand operation (Mudhoo, 2012), accounting for up to 33 % of waste biomass conversion technology.

Several scientific teams presented their reports, or single statements, on how to experimentally analyze and to define predicting models allowing to estimate specific energy requirements for mechanical size-reduction of lignocellulosic biomass. No comprehensive overview serves a reader information on estimating the energy demand when designing a size reduction machine or managing techno-economic studies of lignocellulosic biorefineries. This mini-review is scoped to define the mechanical size reduction principle, present and critically discuss comminution laws and empiric modelling equations predicting specific energy requirements for particle size reduction in dependence on biomass characteristics and the technical set-up of a size reduction machine.

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2. Mechanical size reduction of lignocellulosic biomass: A mini-review and discussion

Identifying mechanical properties of a raw sample, defining a suitable size reduction principle, and its technical set-up provided by process configuration of size reduction machine belongs among the key steps affecting efficiency and specific energy requirement of biomass size-reduction step.

2.1 Size reduction principles

The industrial portfolio of size reduction machines offers several grinders and mills that vary with size reduction principles. The mechanical size reduction always occurs between suitable geometrically arranged size-reduction working tools. Alternatively, it applies a dynamic effect caused by an impact on a solid surface or collisions between particles with each other. The principles of cutting, shearing (Miu et al., 2004), compression, tearing (Yu et al., 2003), and breaking (Schubert and Bernotat, 2004) were recognized as dominant size reduction principles to comminute lignocellulosic biomass, as presented in Figure 1. The right choice of size reduction machines must always be based on an efficient size reduction principle or on mutual combinations of several ones that ensure energy-efficient biomass comminution of given mechanical properties.

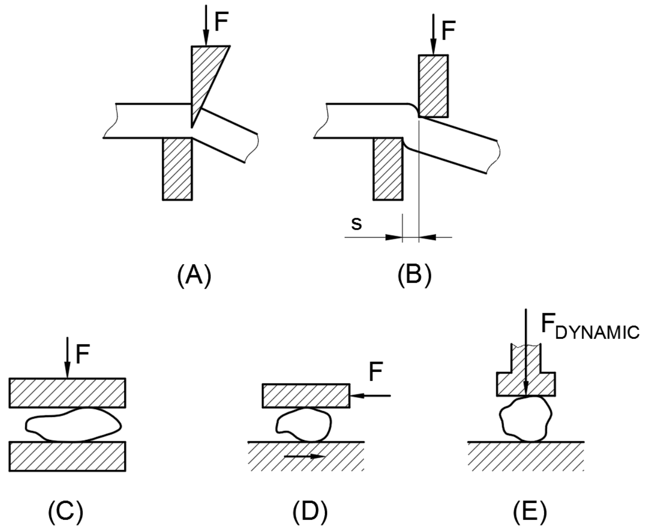

Figure 1: The size reduction principles for lignocellulosic biomass - (A) cutting, (B) shearing, (C) compression, (d) tearing, (e) breaking, F: force, s: clearance, A, B adopted from Miu et al. (2004), C, D, E – adopted from Rieger et al. (2005).

Kratky and Jirout (2011) identified that the knife, hammer, or disc mills are conventional size reduction machines to comminute lignocellulosic biomass of native moisture. These authors also stated that the specific energy requirement of size reduction depends on targeted size reduction ratio (initial over final characteristic particle size), on biomass properties (chemical composition, mechanical properties, moisture), and mill variables (geometrical set-up of working tools, rotor revolutions, drum screen sieve size). It is known that material behaviour generally affects the specific energy demand of size reduction. Lignocellulosic biomass usually evinces brittle, elastic-plastic or elastic-viscous behaviour at ambient temperatures (Miu et al., 2006) primarily affected by biomass moisture (Schubert and Bernotat, 2004). It must be noted that the elastic-based mechanic behaviour gives biomass the ability to withstand the action of compressive and shear forces concerning increase in specific energy demand compared to brittle-based behaviour (Hoque et al., 2007). Each biomass type can be characterized by particle size distribution, mean particle size, moisture content, and mechanical properties such as Young's modulus and tensile or shear stress (Miu et al., 2006). However, the mechanical properties of lignocellulosic materials are difficult to determine due to their composition and moisture (Yu et al., 2003), causing un-isotropic mechanical behaviour. Thus, the specific energy requirement cannot be directly determined by calculation but must be obtained experimentally followed by a precise modelling approach.

2.2 Predicting specific energy requirements for mechanical size-reduction

Specific energy demand for biomass size reduction usually ranges in units or low decimals of kWh t^{-1} (Kratky and Jirout, 2011). Bitra et al. (2009) presented specific energy requirements of 7.57, 8.87, and 10.53 kWh t^{-1} for knife milled for switchgrass, corn stover, and wheat straw, for their size reduction from native size to 25.4 mm under native moisture. Yu et al. (2003) determined specific energy demands of 51.55, 39.59 and 10.77 kWh t^{-1}

to comminute wheat straw by hammer mill from particle size 20-50 mm to 0.794, 1.588, and 3.175 mm. Mani et al. (2004) serve a specific energy requirement of 11 kWh t^{-1} for corn stover and 27.6 kWh t^{-1} for switchgrass, all reduced at a screen size of 3.2 mm from chopped size 25-50 mm. The papers typically present single values of specific energy demand for given experimental conditions with no more in-depth analysis of energy demand modelling. The traditional theory of comminution offers the general models known as Kick, Bond, or Rittinger comminution laws. These comminution models are based on the fundamental assumption that specific energy requirement e (kWh t^{-1}) for biomass size reduction is inversely proportional to particle size D (mm) powered to the parameter r (-), as expressed by Eq. 1. The symbol C represents a general integration constant.

$$\frac{de}{dD} = -\mathrm{C} \cdot D^{-r} \tag{1}$$

The Kick theory expresses the energy demand as the needed size reduction energy to ensure compression of biomass particle resulting by its elastic deformation followed by its crack. The r parameter is equal to 1 for this theory. Implementing r parameter equal to one into Eq. 1, the Kick empirical model is formed as expressed by Eq. 2. Studying the equation, it is evident that the specific energy demand is directly proportional to the size reduction ratio, i.e., the input particle size D_{IN} divided by output one D_{OUT}. The symbol C_K (kWh t^{-1}) is usually called the model's Kick constant. The symbol P (W) represents active power and $\dot{m}$ (kg s^{-1}) biomass flowrate.

$$e = \frac{P}{\dot{m}} = C_K \cdot ln\frac{D_{IN}}{D_{OUT}} \tag{2}$$

The Bond theory supposes that the size reduction energy required for crack propagation is proportional to its length. The r parameter is equal to 1.5 for this theory. The implementation of r = 1.5 into Eq. 1 results with the Bond empirical model as presented by Eq. 3. The symbol C_B (kWh $mm^{0.5}$ t^{-1}) is the Bond model's constant.

$$e = \frac{P}{\dot{m}} = 2 \cdot C_B \cdot \left(\frac{1}{\sqrt{D_{OUT}}} - \frac{1}{\sqrt{D_{IN}}}\right) \tag{3}$$

The Rittinger comminution law assumes that the needed size reduction energy is directly proportional to the increase in particle surface. The r parameter is equal to 2 for this theory. The implementation of r = 2 into Eq. 1 results in the Rittinger empirical model expressed by Eq. 4. The symbol C_R (kWh mm t^{-1}) symbolizes the Rittinger constant of the model.

$$e = \frac{P}{\dot{m}} = C_R \cdot \left(\frac{1}{D_{OUT}} - \frac{1}{D_{IN}}\right) \tag{4}$$

Little papers were dedicated to fitting and testing the precision of the above-presented comminution laws to model the relationship between experimentally identified specific energy requirements on hammer- or knife-milled biomass particle size characteristics. No information was found regarding the specific energy demand of biomass comminution by disc or ball mills. Such analyses were already published for hammer-milled alfalfa (Ghorbani et al., 2010), hammer-milled douglas-fir forest residuals presented by Liu et al. (2020) and Wang et al. (2008), for hammer-milled spruce, pine, beech or oak chips (Temmerman et al., 2013), for knife-milled wheat straw (Kratky et al., 2022), and beech chips (Kratky et al., 2021). All these reports stated that Kick theory, as defined by Eq. 2, is not suitable for defining a prediction model determining specific energy requirements related to change in particle size characteristics of a hammer- or knife-milled biomass due to its poor precision. The same authors also presented the same statements for the validity of Bond's comminution law, excepting Liu et. (2020), who defined the modelling approach for hammer-milled Douglas fir residues as presented in Table 1. Tangirala et al. (2014) highlighted that the Bond comminution law precisely fitted for hammer- or pin-milled turmeric, cinnamon and coriander to spicy powders.

Regarding Table 2, the Rittinger comminution theory was a suitable tool to describe a prediction model determining specific energy requirements related to change in particle size characteristics of a hammer- or knife-milled biomass. Its validity was reached for alfalfa, wheat straw or several wood chips species, all for the native moistures of biomass up to 25 wt %. It means that biomass particles evince a brittle behaviour. It means that energy needed for their size reduction is directly proportional to an increase in the specific surface. Another approach in specific energy demand modelling is represented in Table 3. Analyzing the reviewed models, it is evident that most authors apply simple regression analysis of parametric curves to define the mutual relationship between specific energy requirements and particle size characteristics. The linear (Mani et al., 2004), polynomic (Mani et al., 2004) or power (Eisenlauer and Teipel, 2021) based regression models were presented without any physical interpretation, all concerning biomass moisture, size reduction ratio, screen size, feed rate, rotor revolutions and their mutual combinations, see Table 3. It is evident that the authors fit suitable regression curves to experimental data without any physical background, or they apply comminutions law to describe the mutual relationship between specific energy demand and particle size characteristics. However, a generalized approach to correlating a general biomass species model is still missing. Kratky and Jirout (2022) attempted to develop a modelling approach that predicts specific energy requirements on biomass properties (flowrate, moisture, shear strength, input and output particle sizes) and mill variables.

Table 1: The specific energy modelling approaches based on Bond's theory.

Biomass	Mill	Model and its limits	Reference
douglas-fir forest residuals	hammer	$e = (0.0039 \cdot M + 0.0259) \cdot \left(\frac{1}{\sqrt{D_{50OUT}}} - \frac{1}{\sqrt{D_{50IN}}}\right)$ *6.7-27.8 % wt M, 0.171-2.200 mm D_{50}, R and F not defined*	Liu et al. (2020)

Table 2: The specific energy modelling approaches based on Rittinger's theory.

Biomass	Mill	Model and its limits	Reference
alfalfa	hammer	$e = 46.0 \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ *13.3 % wt M, 0.317-1.960 mm D_{50}, 360 rpm R, 6.6 kg min^{-1} F*	Ghorbani et al. (2010)
beech chips	knife	$e = 25.9 \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ for 0.5 % wt *M* $e = 54.1 \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ for 7.5 % wt *M* $e = 58.2 \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ for 16.0 % wt *M* *0.31-3.09 mm D_{50}, 20.4 m s^{-1} R, 0.4-2.1 kg min^{-1} F*	Jirout and Kratky (2021)
beech chips	hammer	$e = 5.11 \cdot M \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ *1.1-21.7 % wt M, 0.46-5.83 mm D_{50}, 2800 rpm R, F not defined*	Temmerman et al. (2013)
douglas-fir wood	hammer	$e = 104.5 \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ *11.0 % wt M, 0.035-7.81 mm D_{50}, 115 m s^{-1} R, 0.15-1.83 kg min^{-1}*	Wang et al. (2018)
oak chips	hammer	$e = 8.54 \cdot M \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ *1.4-22.4 % wt M, 0.40-4.93 mm D_{50}, 2800 rpm R, F not defined*	Temmerman et al. (2013)
pine chips	hammer	$e = 9{,}65 \cdot M \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ *4.9-20.8 % wt M, 0.40-4.93 mm D_{50}, 2800 rpm R, F not defined*	Temmerman et al. (2013)
spruce chips	hammer	$e = 11.85 \cdot M \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ *1.5-21.3 % wt M, 0.44-7.38 mm D_{50}, 2800 rpm R, F not defined*	Temmerman et al. (2013)
wheat straw	knife	$e = 19.9 \cdot \left(\frac{1}{D_{50OUT}} - \frac{1}{D_{50IN}}\right)$ *4.6 % wt M, 0.36-2.29 mm D_{50}, 7.8-15.6 m s^{-1} R, 0.4-2.1 kg min^{-1} F*	Krátký a Jirout (2020)

e – specific energy demand (kWh t^{-1}), M – moisture (% wt), D_{50} – characteristic particle size at a cumulative mass fraction of 50 wt %, D_{50IN} – characteristic particle size D_{50} before milling (mm), D_{50OUT} – characteristic particle size D_{50} after milling (mm), R – rotor speed (rpm or m s^{-1}), $\dot{m}$ – mass feed rate (kg min^{-1}).

Table 3: The specific energy modelling approaches applying regressed parametric curves.

Biomass	Mill	Model and its limits	Reference
beech chips	knife	$e = (-0.0142 \cdot M^2 + 0.5683 \cdot M + 4.667) \cdot SRR$ *1.5-34.0 wt % in M, 2.66-7.46 mm D_{50}, 5 m s^{-1} R, 0.1 kg min^{-1}*	Eisenlauer and Teipel (2021)
beech chips	hammer	$e = (-0.008 \cdot M^2 + 0.4268 \cdot M - 0.1186) \cdot SRR^{(0.0004 \cdot M^2 - 0.0270 \cdot M + 2.1185)}$ *1.5-34.0 wt % in M, 0.87-7.46 mm D_{50}, 26.6 m s^{-1} R, 0.1 kg min^{-1}*	Eisenlauer and Teipel (2021)
corn stover	knife	$e = 20.383 - 0.519 \cdot SC - 8.919 \cdot F + 0.134 \cdot R - 0.242 \cdot SC \cdot F - 0.024 \cdot F \cdot R - 0.004 \cdot R \cdot SC + 0.500 \cdot F^2$ *9 wt % in M, 12.7-50.8 mm SC, 250-500 rpm, 1-11 kg min^{-1}*	Bitra et al. (2009)
corn stover	hammer	$e = 5.31 \cdot SC^2 - 30.86 \cdot SC + 55.45$ *12.0 wt % in M, 60 rpm, 0.8-3.2 mm SC, R undefined*	Mani et al. (2004)
spruce chips	knife	$e = (-0.0041 \cdot M^2 + 0.4018 \cdot M + 3.7317) \cdot SRR$ *1.5-34.0 wt % in M, 3.18-6.59 mm D_{50}, 5 m s^{-1} R, 0.1 kg min^{-1}*	Eisenlauer and Teipel (2021)
spruce chips	hammer	$e = (0.0066 \cdot M^2 - 0.0438 \cdot M + 1.800) \cdot SRR^{(-0.0003 \cdot M^2 - 0.0091 \cdot M + 1.7384)}$ *1.5-34.0 wt % in M, 1.10-6.59 mm D_{50}, 26.6 m s^{-1} R, 0.1 kg min^{-1}*	Eisenlauer and Teipel (2021)
switchgrass	knife	$e = 24.922 - 0.112 \cdot SC - 6.021 \cdot \dot{m} + 0{,}054 \cdot R - 0.021 \cdot SC \cdot \dot{m} - 0.005 \cdot \dot{m} \cdot R + 0.002 \cdot SC^2 + 0.502 \cdot \dot{m}^2$ *9 wt % in M, 12.7-50.8 mm in SC, 250-500 rpm, 1-11 kg min^{-1}*	Bitra et al. (2009)
switchgrass	hammer	$e = -16.45 \cdot SC + 76.52$ *8.0 wt % in M, 60 rpm, 0.8-3.2 mm SC, R undefined*	Mani et al. (2004)
wheat straw	knife	$e = 28.936 - 0.445 \cdot SC - 7.130 \cdot \dot{m} + 0.076 \cdot R - 0.068 \cdot \mathrm{SC} \cdot \dot{m} - 0.009 \cdot \dot{m} \cdot R - 0.00005 \cdot R \cdot SC + 0.500 \cdot \dot{m}^2$ *9 wt % in M, 12.7-50.8 mm in SC, 250-500 rpm, 1-11 kg min^{-1}*	Bitra et al. (2009)
wheat straw	hammer	$e = -4.07 \cdot SC^2 + 7.48 \cdot SC + 41.95$ *12.1 wt % in M, 60 rpm, 0.8-3.2 mm SC, R undefined*	Mani et al. (2004)

3. Conclusions

Mechanical size reduction belongs among the crucial pretreatment steps in lignocellulosic biorefineries. Biomass particle size in units or lower tens of millimetres is always demanded to increase subsequent biomass treatment process efficiency. Knife mills, the least energy-demanding one, or hammer mill were the commonly used size reduction machines to comminute lignocellulosic biomass in a native state. Specific energy demand for biomass size reduction usually ranges in units or low decimals of kWh t^{-1}. Two general modelling approaches were identified to predict specific energy requirements for biomass comminution. The conventional Rittinger's comminution law or interpolated regression (linear, polynomic or power-based) models fitted to experimental data without any physical interpretation are used to model specific energy demand and particle size characteristics. The Rittinger's constant reaches the values of lower tens (kWh mm t^{-1}) dependent on biomass species and machine variables. However, a generalized approach to correlating specific energy demand on biomass species and mill variables is still missing. Therefore, there is a need to develop and calibrate a generally valid model that predicts specific energy demand concerning biomass properties and machine variables. This information is essential for size reduction machine design and performing techno-economic studies of lignocellulosic biorefineries, energy balancing especially.

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