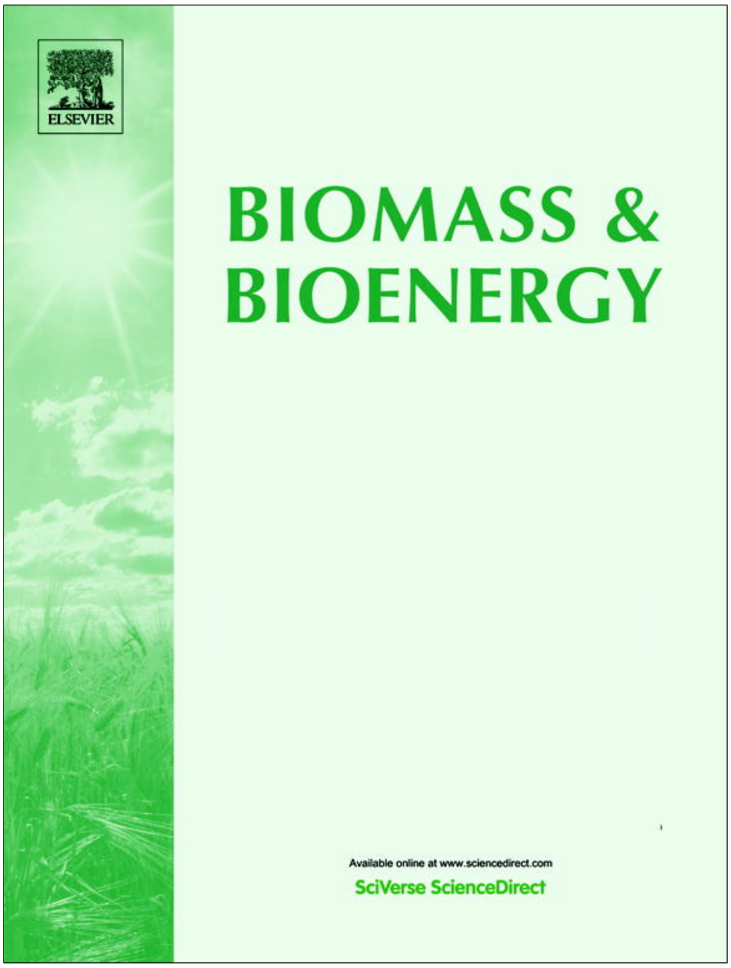
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BIOMASS AND BIOENERGY 56 (2013) 70–81

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# Von Rittinger theory adapted to wood chip and pellet milling, in a laboratory scale hammermill

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ARTICLE INFO

Article history:
Received 24 April 2012
Received in revised form
18 December 2012
Accepted 26 April 2013
Available online

Keywords:
Milling
Wood chips
Pellets
Grindability
Von Rittinger
Kick

ABSTRACT

The study draws upon the milling theories developed for the ore processing industry (Von Rittinger, Kick and Bond theories) in order to define a method for characterising wood chip and pellet energy consumption during milling.

Energy consumption during wood milling depends on three main factors: the material moisture content, the particle size difference between the feed and the milled product, and the material itself. The latter may be characterised by a single parameter based on an adaptation of Von Rittinger's constant.

A relation characterising wood pellet energy consumption as a function of the particle size distribution of the pellet ingredients and the milled pellets is proposed. This is characteristic of each type of pellet for each moisture content value considered.


## 1. Introduction

The international drive to cut greenhouse gas emissions, carbon dioxide in particular, has prompted many electricity producers to convert some of their pulverized coal or gas plants to biomass co-combustion plants. There is even an example of a plant being converted to run on wood pellets exclusively [1]. Adding biomass to fossil fuels has a number of advantages. From an environmental point of view using biomass reduces fossil $CO_2$, $SO_x$ and $NO_x$ emissions rapidly. Moreover, from a technical point of view boiler efficiency increases and lower fuel cost makes the plants more cost-effective [2–4].

Some power plants use biomass (generally wood-derived) in pulverized form, which requires milling before use to produce wood particles that have the requisite aerodynamic and combustion properties to be used in the process. In such systems the characteristics of the biomass particles are vitally important as they impact upon feeding, combustion kinetics, the combustion residue volume and the hearth temperature [5–8].

For most such co-combustion units the specification requires all of the particles to pass through a 6.34 mm mesh and the majority to pass through a 3 mm mesh [4]. However, some consumers sometimes apply stricter specifications [1,9].

Grinding chips and pellets can pose problems, however. There is a lack of data for dimensioning the mill when designing power plant supply circuits. Conversely, in existing circuits, acceptance of new materials requires true scale pilot projects. More generally, little research appears to have been done overall into fine milling of biomass.

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0961-9534/$ – see front matter 
http://dx.doi.org/10.1016/j.biombioe.2013.04.020

This paper therefore attempts to identify ways of characterising the energy requirements for wood chip and pellet milling. To that end, existing knowledge of biomass milling is assessed in the light of practice in other sectors such as the food and ore processing industries.

### 1.1. *Milling theories*

Milling theory is based on the relation between energy consumption and the product particle size obtained from a given feed size. In Eqs. (1)–(5), $E_{1-2}$ (specific energy) is the milling energy needed for a particle size reduction from $x_1$ to $x_2$, per unit of mass; $x$ is a particle size distribution characteristic (for example, Q80 or Q50 – the passing size of 80% or 50% of the measured material, respectively – the 80 or 50 quantile of the distribution), the indices 1 and 2 of $x$ ($x_1$, $x_2$) indicate that $x$ relates to the feed and the milled product, respectively, $n$ is an exponent expressing the process magnitude, and $C$ is a constant characterising the material to be milled, the units of which balance the equation.

Historically, a number of milling theories have been proposed [10]. Of these, three deserve closer attention as they have come down through the generations and are still cited in many publications today.

Von Rittinger theory (1867) is the oldest. This states that the new surface area generated is directly proportional to the energy required for size reduction. As the surface area of a quantity of particles of uniform diameter $x$ is proportional to $1/x$, the energy required for size reduction is therefore also proportional. It is expressed by the general formula (Eq. (1))

$$E_{1-2} = C_{VR}\left(\frac{1}{x_2} - \frac{1}{x_1}\right) \quad (1)$$

where $C_{VR}$ is a constant characteristic of the material.

Kick (1885), meanwhile, postulated that the work required is proportional to the volume reduction of the particles concerned. Kick's equation is shown below:

$$E_{1-2} = C_K(\ln(x_1) - \ln(x_2)) = C_k \ln\frac{x_1}{x_2} \quad (2)$$

where $C_K$ is a constant characteristic of the material. The ratio $x_1/x_2$ is sometimes called the reduction ratio.

From a physical point of view, Bond's theory (1952) assumes that the energy transmitted to a body by a compressive force is initially distributed in the mass and is proportional to $x_1^3$, but as soon as surface cracking starts, that energy is concentrated in the cracks and is then proportional to $x_1^2$. Consequently, it is assumed that grinding proper is halfway between $x_1^2$ and $x_1^3$.

According to this theory, for particles of similar shape, the crack length is equivalent to the square root of the surface. The milling energy being proportional to the crack length, it is expressed according to (3) as:

$$E_{1-2} = C_B\left(\frac{1}{\sqrt{x_2}} - \frac{1}{\sqrt{x_1}}\right) \quad (3)$$

where $C_B$ is a constant characteristic of the material.

Von Rittinger's, Kick's and Bond's laws were collated by Charles [11], who stated that the relations between energy $E$ and particle size characteristic $x$ established by these three authors are special forms of the same differential equation (Eq. (4)).

$$dE = -C\frac{dx}{x^n} \quad (4)$$

The exponent $n$ of $x$ takes the values of 2, 1 and 1.5 for the Von Rittinger, Kick and Bond theories, respectively.

Hukki [12] then showed for the mineral industry that each of these values corresponds to a relatively restricted particle size distribution range and that the exponent is not constant but depends on the particle size distribution level $x$ itself, as expressed by Eq. (5).

$$dE = -C\frac{dx}{x^{f(x)}} \quad (5)$$

That relation would subsequently be developed and refined. Morell [13] postulated that the constant $C$ is itself dependent on the particle size distribution and is not the same for all rocks. Stamboliadis [14] proposes a relation where the effects of particle size distribution are expressed in the form of a theoretical frequency distribution.

With a view to their application to wood size reduction, the above studies have the advantage of estimating the energy consumption of a grinding circuit from a small number of parameters. These are applicable to a wide range of different materials, from a hardness point of view at least. Even though they were developed for the kind of mill used in the mineral industry, they indicate that a relationship may be established between the energy consumed by milling a material and the particle size distribution of the product and of the raw material.

### 1.2. *Biomass grinding*

Relatively little information is available in the literature on energy consumption for biomass grinding. Mani et al. [15] quote a few authors who studied this in the 1980s. More recently, Vigneault et al. [16,17] published energy consumption data for corn grinding. Since then, the publications on this topic have been mainly the work of few authors, including Mani [9,18–23]. Also, the development of the wood torrefaction technique and its impact on the grindability of biomass [24–26] provides some measurements of energy consumption in wood size reduction [27]. Lastly, the comminution of Miscanthus, switchgrass, energy cane and poplar was recently studied by Miao [28]. The data published by these different authors are summarised in Table 1.

The work of Vigneault et al. [16,17] involves a comparison of corn grinding energy consumption according to the hammer design and type of screen fitted to the grinder in a commercial mill. The research shows the significant effects of hammer design and rate on energy consumption. All other things being equal, measured consumption varied from 10 to 12 kWh/tonne for thin and conventional hammers, respectively. The type of screen used also affected grinding energy consumption.

Laskowski et al. [19–21] established a relationship between the compression behaviour of seeds and energy consumption in a laboratory-scale mill. This work clearly shows the effects of moisture content and comminuted material on energy

**Table 1 – Energy required to grind different biomasses ($E_{cn}$): some published data (index 1, feed; index 2, product; PSD, particle size distribution; *H*, moisture content; *H* Pc and *H* Pb, considered material moisture content; Gd, screen; GM, geometric mean; MS, average; Q50, quantile 50; Q95, quantile 95; *P*, relative energy measurement; *N*, net biomass; *G*, overall grinding circuit; NS, not specified).**

| Material | PSD in ($x_1$-mm) | PSD out ($x_2$-mm) | *H*1 (%) | *H*2 (%) | *P* | $E_{cn}$ (kWh/t) |
|---|---|---|---|---|---|---|
| Source: [15] | | | | | | |
| Wheat straw | GM: 7.67 | Gd 0.8; 1.6; 3.2 | NS | 8.3 | N | 11.4–51.6 |
| | GM: 7.67 | Gd 0.8; 1.6; 3.2 | NS | 12.1 | N | 24.7–45.3 |
| Barley straw | GM: 20.52 | Gd 0.8; 1.6; 3.2 | NS | 6.9 | N | 13.8–53.0 |
| | GM: 20.52 | Gd: 0.8; 1.6 | NS | 12.0 | N | 27.1–99.5 |
| Corn stover | GM: 12.48 | Gd 0.8; 1.6; 3.2 | NS | 6.2 | N | 7.0–22.1 |
| | GM: 12.48 | Gd 0.8; 1.6; 3.2 | NS | 12.0 | N | 11.0–34.3 |
| Switchgrass | GM: 7.15 | Gd 0.8; 1.6; 3.2 | NS | 8.0 | N | 23.8–62.6 |
| | GM: 7.15 | Gd 0.8; 1.6; 3.2 | NS | 12.0 | N | 27.6–58.5 |
| Source: [18] | | | | | | |
| Poplar | $Q_{50}$: 8.0 | $Q_{95}$: 1.0 | 11.8 | 8.1 | G | 82–89 |
| Pine | $Q_{50}$: 9.2 | $Q_{95}$: 1.0 | H Pc | HPc – 34% | G | 113.2–119.1 |
| Pine bark | $Q_{50}$: 8.25 | $Q_{95}$: 1.0 | HPb | HPb – 9% | G | 18.1–23.6 |
| Source: [27] | | | | | | |
| Poplar | NS | MS: 0.2–1.2 | 13 | NS | N | 100–375 |
| Poplar | NS | MS: 0.2–1.2 | 10 | NS | N | 50–150 |
| Source: [19–21] | | | | | | |
| Beans | NS | Grid 1.0 | 10–18 | NS | NS | 27–64 |
| Peas | NS | Gd: 1.0 | 10–18 | NS | NS | 23–50 |
| Lupins | NS | Gd: 1.0 | 10–18 | NS | NS | 70–144 |
| Vetch | NS | Gd: 1.0 | 10–18 | NS | NS | 15–36 |
| Source: [16] | | | | | | |
| Corn | NS | GM: 0.49–0.51 | NS | NS | NS | 10.0–12.4 |
| Source: [9] | | | | | | |
| Pine chips | 8 | Gd: 3; 4; 6 | 10–15 | 8.6–9.3 | G | 36–53 |
| Source: [22] | | | | | | |
| Cynara pellets | NS | $Q_{50}$: 0.5–0.25 | 12.0 ± 0.3 | 11.0 ± 05 | G | 6.1–35.0 |
| Cynara stem | NS | $Q_{50}$: 0.77–0.27 | 10.4 ± 0.2 | 9.5 ± 0.6 | G | 15.0–79.9 |
| Cynara plant | NS | $Q_{50}$: 0.71–0.24 | 13.0 ± 0.8 | 11.0 ± 0.7 | G | 14.2–60.8 |
| Source [23] | | | | | | |
| Switchgrass | GM: 8.3 | GM: 0.43–0.65 | 9.0 ± 0.5 | NS | G | 31.8–46.0 |
| | GM: 8.3 | GM: 0.43–0.65 | 9.0 ± 0.5 | NS | N | 14.7–18.5 |
| Wheat straw | GM: 7.1 | GM: 0.66–0.83 | 9.0 ± 0.5 | NS | G | 34.8–46.8 |
| | GM: 7.1 | GM: 0.66–0.83 | 9.0 ± 0.5 | NS | N | 14.6–19.1 |
| Corn stover | GM: 8.3 | GM: 0.53–0.63 | 9.0 ± 0.5 | NS | G | 28.8–47.7 |
| | GM: 8.3 | GM: 0.53–0.63 | 9.0 ± 0.5 | NS | N | 13.0–19.8 |

consumption. For a given material, the higher the grain moisture content, the higher the grinding energy consumption. Measured consumption levels ranged from 15 to 144 kWh/tonne.

The milling characteristics of three forms of *Cynara cardunculus* L., were described by Gil et al. [22] in a study on the use of this raw material as solid biofuel. The moisture content of the considered materials is between 9.5% and 13.0%. Trials were made in a hammermill equipped with interchangeable screens perforated by 5, 2, 1 and 0.5 mm mesh. The work shows the influence of the screen on the global electrical consumption of the milling circuit. It is as well observed that *C. cardunculus* L. pellets need less energy to be milled (6.1–35 Wh/kg depending on the used screen) if compared to whole plants and stems (15.0–79.9 Wh/kg and 14.2–60.8 Wh/kg, respectively).

The milling of switchgrass, wheat straw and corn stover in a hammermill equipped with a 3.2 mm mesh screen has been studied by Bitra et al [23]. Two hammer types and five rotation speeds of the rotor are compared on an electrical consumption basis, considering total specific energy and effective specific energy (total energy from which the empty consumption of the hammermill has been taken away). The global specific energy consumption (empty and in charge) is influenced by the rotor speed and ranges from 31.8 to 46.0 Wh/kg, from 34.8 to 46.8 Wh/kg and from 28.8 to 47.7 Wh/kg for switchgrass, wheat straw and corn stover, respectively. In the same test conditions, effective specific energy is less influenced by the hammermill settings. In this case, the recorded consumption range from 14.7 to 18.5 Wh/kg, from 14.6 to 19.1 Wh/kg and from 13.0 to 19.8 Wh/kg for switchgrass, wheat straw and corn stover, respectively.

In a study designed to assess the pros and cons of combining wood torrefaction and densification (pelletisation), Bergman et al. [27] compared the energy consumption when grinding dry and moist poplar with the values for torrefied wood, using a disk chipper. According to the particle size distribution (average particle size 0.2–1.2 mm), grinding oven-dry wood consumed between 50 and 150 kWh/tonne, whereas slightly moister wood (10–13%) required a consumption range of 100–325 kWh/tonne, for the same particle size distribution range. These measurements also show a clear trend towards higher energy consumption for the finest degrees of milling.

Wood size reduction has also been studied by Esteban et al. In an initial paper [9] on the energy efficiency of a pellet production circuit, the raw material comprised Norway pine logging residue chips conditioned to a homogeneous moisture content of between 10% and 15% that had undergone initial crushing in a hammermill fitted with a perforated screen with 8 mm diameter mesh. This material then underwent further refining in the same mill with 6, 4 or 3 mm screen sizes, alternatively. The total energy consumption for each pass was measured and ranged from 29 to 53 kWh/tonne.

In a second paper Esteban et al. [18] compared the efficiency of different grinding circuits, from an energy consumption point of view in particular. Three materials with similar particle size distributions were tested: poplar chips (Q50:8 mm), pine chips (Q50:9.3 mm) and pine bark (Q50:8.25 mm).Twelve one-stage or multi-stage material preparation circuits were assayed with the aim of producing particles that could be used to feed pulverized fuel burners (Q95: 1.0 mm and Q12: 0.125 mm).The overall energy consumption values for the different alternatives were measured and compared with one another. It is to be noted that few of the alternatives tested achieved the target particle size distribution. However, the energy consumption of the different material/grinding circuit combinations varied more from one material to another than from one process to another. The average overall energy consumption for all the processes tested for grinding poplar was 85.4 kWh/tonne (with a standard deviation of 4.9 kWh/tonne), the value for pine chips was 118.5 kWh/tonne (standard deviation 6.2 kWh/tonne) and that for pine bark was 19.7 kWh/tonne (with a standard deviation of 3.9 kWh/tonne).The authors also noted that grinding greatly reduced the material moisture content in the case of all three materials tested.

Mani et al. studied the energy consumption for grinding biomass [15]. The authors looked at various factors that could affect grinding energy consumption. Material properties listed include the type of biomass itself, moisture content, particle size distribution (before and after grinding), bulk density and particle density. The equipment itself can also have an impact, for example, the type of grinder used, the settings, feed rate.

Using a low-powered grinder Mani et al. studied the net energy consumption when grinding four materials (wheat straw, barley straw, corn stover and switchgrass). The particle size distribution was expressed in terms of the geometric mean (switchgrass: 7.15 mm; wheat straw 7.67 mm; corn stover: 12.48 mm; barley straw 20.52 mm). Three screen sizes were used to grind the biomass, which was pre-conditioned at two moisture content levels (approx. 8% and 12%). Measured consumption data varied from 11.04 kWh/tonne to 62.55 kWh/tonne according to the above influencing factors. On the basis of these data the authors defined relations between the grinder screen size and energy consumption. These are linear for the driest materials and polynomial for the highest moisture content.

Mani et al. were probably the first to formalise the relationship between energy consumption and an expression of product particle size distribution (screen size) in biomass grinding. Miao confirmed the effects of moisture content on grinding energy consumption. Moreover, he proposed a power type relation to express the energy consumption according to the screen diameters used in comminution [28].

### 1.3. *What milling theory for biomass?*

From an analysis of the available literature it appears that the material ground and its origin affect the grinding, giving rise to a specific relationship between energy consumption and particle size distribution for a given system. This has been shown in the case of ores but little work has been done on biomass. For example, the particle size distribution of the starting material is not always measured and, when it is, the deviation from the product particle size distribution is rarely considered when stating the results. However, the particle size distribution deviation between the initial state and final state of the material is the very basis of milling theory in the mineral industry.

Moisture content is probably the primary additional influencing factor to be taken into consideration when studying the use of biological materials, i.e., biomass. Grinding is no exception. However, the scant data available on this topic are sometimes contradictory. All the same, it appears appropriate to take the view that the higher the moisture content of a material, the more energy will be consumed in grinding it.

No data are available in the literature concerning energy consumption for grinding wood pellets. The influencing factors are likely to be the same as with other types of biomass. However, some specific properties of biofuel pellets need to be considered, namely the durability and particle size distribution of the raw material, both included in the specification by the main power plant pellet users. The pellet raw material undergoes a final particle size reduction before use in the power plant. This reduction is probably a big energy consumer, compared with that which could be expressed in terms of durability. The cohesion of the material within the particles forming the pellets is in fact likely to be greater than the cohesion between the particles.

This study therefore sets out firstly, to assess the possibility of using ore milling theories to characterise biomass grinding and identify the most appropriate parameters for the purpose. Secondly, to propose a biomass grinding procedure and model that will produce comparable results for different forest species. And lastly, to assess the applicability of the proposed model to milling of pellets.

## 2. Material and methods

### 2.1. Test bench

An outline diagram of the equipment used for the purpose of this study is provided in Fig. 1.The mill was equipped with six swinging metal hammers (flails) equally spaced around a 100 mm diameter steel disc. The centre of the axis around which the hammers swung was 12.5 mm from the edge of the disc. The hammers were T-shaped with a 5 mm side cross-section. The swinging part of the hammers was 37.5 mm in length from the centre of the axis of rotation to the base of the T part perpendicular to it. The milling chamber had an inside diameter of 190 mm and its width was 55 mm. An interchangeable curved screen with an inside diameter of 160 mm and 55 mm wide was centred within the milling chamber. The rate of rotation of the drive shaft was 2800 rpm. The electric motor developed a rated power of 1.1 kW. Six different screens were used on the hammermill for the purpose of the experiment. The screens were perforated with round meshes of diameter 8, 6, 5, 4, 3 and 2 mm.

The grinder was fed manually at a regular rate, taking care not to overload it. The feed rate therefore varied according to the characteristics of the test materials. The mill discharged into a box from which the grind was collected in order to determine the particle size distribution and moisture content. The grinder power supply leads were connected to a HIOKI 316920 power demand analyzer to measure and record the differential potential (V), current intensity (A), grinder instantaneous power draw (W), frequency (Hz) and time (s). The measuring interval was 1 s. The equipment also calculated the energy consumption (Wh) for grinder operation. The data were recorded by a data logger and transmitted to a computer.

### 2.2. Wood chip characteristics

The wood chips used in this research came from two deciduous species and two coniferous species: oak (*Quercus* sp.), beech (*Fagus sylvatica L.*), spruce (*Picea abies (L.) Karst*) and pine (*Pinus* sp.). Chips were prepared from wood rafters (without bark and preparatory drying) produced in Belgian sawmills, which were chipped using a disc chipper (Van Deale TS 180). Each material was prepared in order to produce five input moisture content classes. The averages for these classes (and the number of observations) are shown in Table 2. They range from 1.1% to 22.4%. The maximum value of the median of the feed particle size distributions ($Q_{50}$ max) is 7.38 mm and the minimum value of the median of the product particle size distributions ($Q_{50}$ min) is 0.40 mm.

### 2.3. Wood chip grinding method

*Five moisture content classes* – to achieve the different moisture content levels (H1–H5, see Table 2) to be grouped into five classes, the fresh chips were air-dried or oven-dried (105 °C, as long as necessary to reach the desired moisture content).To avoid clogging the meshes, in particular the smaller ones, with over-moist material the moisture content levels greater than 25% were disregarded in this experiment.

*Twelve particle size distribution treatments* – initially, the chips underwent preliminary grinding in an industrial grinder before being screened on a 16 mm diameter round mesh screen. The aim of this step was to make the particle size distribution of the test chips compatible with the laboratory-scale mill used. About 8 kg of material was then divided into eight sub-samples of approximately 1 kg. Grinding was carried out using six screens with different mesh diameters. The screen mesh diameters were 8, 6, 5, 4, 3 and 2 mm.

In the course of the grinding protocol (illustrated by Fig. 2) the eight sub-samples (RM 1–8) underwent initial grinding using an 8 mm diameter mesh screen (G8, replicates 1–8).The grind was recovered and reground using screens with mesh of a different diameter. One grinding pass (G8 R1) was performed with a 6 mm screen (G86), 3 passes (G8 R2–4) with a 5 mm screen (G85 R 1–3), 2 passes (G8 R5 and 6) with a 4 mm screen (G84 R 1 and 2), 1 (G8 R7) with a 3 mm screen (G83) and 1 (G8 R8) with a 2 mm screen (G82).

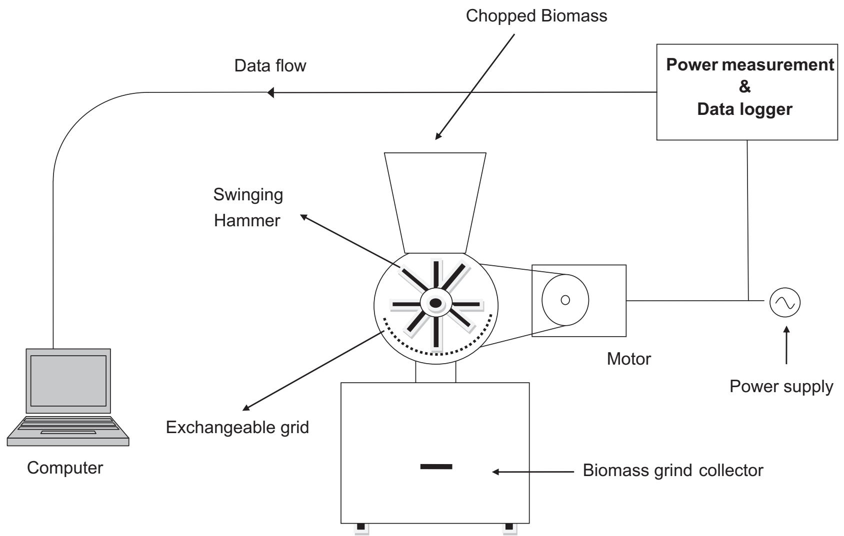


**Fig. 1 – Experimental milling equipment.**

**Table 2 – Moisture content of wood chips tested in grinding trials. *H1*, *H2*, *H3*, *H4* and *H5* (in %) are the average values of the moisture content classes for each material; (*n*) is the number of observations in the class, $Q_{50}$ Max and Min (in mm) are the maximum and minimum medians of the particle size distributions for each species (for all moisture content classes).**

| Coniferous | *H1*% (*n*) | *H2* % (*n*) | *H3* % (*n*) | *H4* % (*n*) | *H5* % (*n*) | $Q_{50}$ Max (mm) | $Q_{50}$ Min (mm) |
|---|---|---|---|---|---|---|---|
| Pine | 4.9 (13) | 9.0 (13) | 13.5 (15) | 17.4 (16) | 20.8 (5) | 4.93 | 0.40 |
| Spruce | 1.5 (12) | 7.0 (13) | 12.2 (16) | 16.1 (13) | 21.3 (8) | 7.38 | 0.44 |
| Deciduous | | | | | | | |
| Oak | 1.4 (13) | 7.8 (15) | 12.4 (14) | 17 (12) | 22.4 (9) | 4.98 | 0.45 |
| Beech | 1.1 (13) | 8.1 (13) | 13.4 (13) | 16.5 (11) | 21.7 (13) | 5.83 | 0.46 |

In each case, the resulting grind was recovered and reground. The grind from the 6 mm screen (G86) was reground on a 4 mm screen (G864) before being recovered again and ground on a 2 mm screen (G8642).

The grind from the 5 mm screen (G85 R 1–3) was ground on different screens, one on the 4 mm screen (G854), one on the 3 mm screen (G853) and one on the 2 mm screen (G852).The grind from the 4 mm screen (G84 replicates 1 and 2) was also ground on different screens, one on the 3 mm screen (G843) and one on the 2 mm screen (G842).

This procedure generated 13 different treatments characterised by particle size distribution differences between the feed particle size distribution and the product particle size distribution. At least one repetition has been performed for each treatment, but the procedure imposed to repeat some treatments more than once: millings with 8 mm (G8), 5 mm (G85) and 4 mm (G84) mesh screen were performed in 8, 3 and 2 replications, respectively. In this case mean values of the repetitions was considered. Considering the five moisture content classes, 62 different treatments have been applied to Pine and Spruce, while 63 have been applied to Oak and Beech. In each trial one sample was taken to measure the moisture content and the particle size distribution before and after grinding. The procedure was repeated for the four selected materials, for each moisture content class.

*Measured data* – when grinding each sub-sample the following data were collected: sample mass (g), idle consumption (Wh) and consumption over the grinding period (Wh), feed particle size distribution (mm – according to the size of the particles this characteristic was determined in accordance with the instructions given in European standards EN 15149:2010-1 or EN 15149:2010-2 [29,30]), the product particle size distribution (mm – measured according to EN 15149:2010-2 [29]), the feed and the product moisture content (% – measured according to EN 14774:2009-2 [31]).

*Collected data* – the following parameters were calculated with the aid of the measured data: $E_{cn}$ = net energy consumption, per kg of dry material input, given by the consumption over the grinding period less the idle consumption (Wh/kg oven-dry); the medians of the material particle size distributions before and after grinding.

*Determination of the most appropriate milling theory to characterise biomass* – based on Charles' relation (4) and knowing the particle size distribution (distribution median) of the material before and after grinding, there is a pair (constant *C* and exponent *n*) which minimises the deviation sum of squares (DSS) between the measured energy consumption values and those estimated with the aid of the model. The average of the exponents *n* thus determined was then compared to the values of that parameter according to the Von Rittinger, Kick and Bond laws (2, 1.5 and 1), in order to select the most appropriate one to express wood grinding energy consumption.

With the parameter *n* fixed, the constant *C* which minimises the deviation sum of squares was then recalculated for each material and each moisture content level.

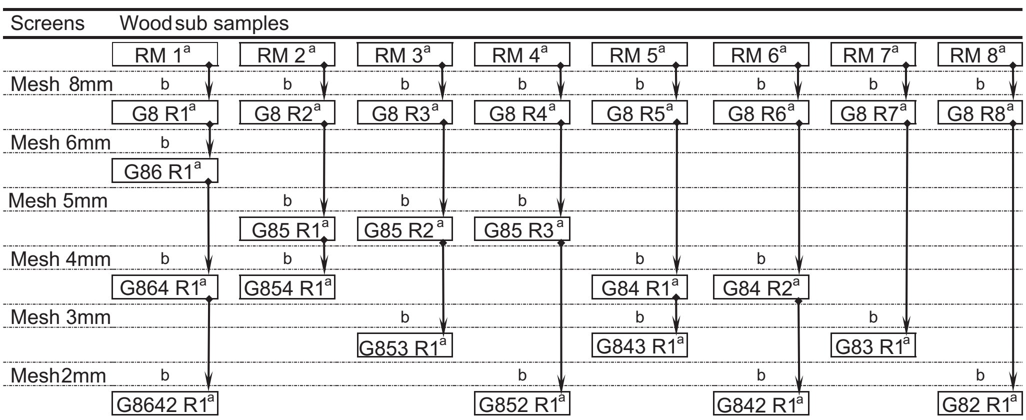


**Fig. 2 – Wood milling experimental plan applied to each moisture content class and wood species combination: (a) mass, moisture content and particle size distribution determination, (b) energy recording for milling from the feed into the product.**

Finally, for each species of wood a linear relation (passing through the origin) between *C* and the average moisture content of the class was determined. The coefficient of that regression line characterised the species and expressed its grindability.

### 2.4. Pellet characteristics

The five batches of commercial wood pellets used in this study were of various origins and their characteristics are shown in Table 3. For each batch, the trials were grouped into two moisture content classes. The averages of the values in those classes (H1 from 0.18% to 0.97% and H2 from 5.71% to 12.44%) are also shown in the table. The following properties were also considered: durability (DU, 98.5% to 99.3%), particle density (PD, 1.23 to 1.32 g/cm$^3$), fines (*F*, 0.12–4.9%), bulk density (BD, 632–722 kg/m$^3$).The median of the particle size distribution of the pellet ingredients (PIPSDQ50, 0.39–1.18 mm) completes the list of properties considered.

### 2.5. Pellets grinding method

*Two moisture content levels* – the nature of the pellets restricts the number of moisture content classes. The pellets were therefore tested at two moisture content levels (moisture content at delivery and after oven drying for 24 h at 105 °C).

*6 particle size reduction levels for whole pellets* – approx. 16 kg of pellets were divided into eight sub-samples (P1–P8). In the course of the grinding protocol (illustrated by Fig. 3) these whole pellet sub-samples were milled using screens of different mesh diameters (8, 6, 5, 4, 3 and 2 mm). The resulting grind (PG8 R1 to R3, PG6, PG5, PG4, PG3, PG2) was collected and then milled again using screens with smaller mesh sizes.

*Sixteen particle size distribution treatments for pre-milled pellets* – the grind from the first sub-sample (PG8 R1) underwent a further three successive millings using the 6, 4 and 2 mm diameter mesh screens (PG86, PG864, PG8642, respectively). The grind from the second sub-sample (PG8 R2) underwent a further three successive millings using the 5, 3 and 2 mm diameter mesh screens (PG85, PG853, PG8532, respectively). The grind from the third sub-sample (PG8 R3) underwent a further two successive millings using the 4 and 2 mm diameter mesh screens (PG84, PG842, respectively).

The grind from the 6 mm screen (PG6) underwent a further three successive millings on the 5, 4, and 2 mm screens (PG65, PG654, PG6542, respectively), the grind from the 5 mm screen (PG5) underwent a further two successive millings on the 3 and 2 mm screens (PG532 and PG532, respectively), the grind from the 4 mm screen (PG4) underwent a further two successive millings on the 3 and 2 mm screens (PG43 and PG432, respectively) and the grind from the 3 mm screen (PG3) underwent a further 1 milling on the 2 mm screen (PG32). The last pellet sub-sample (P8) was milled on the 2 mm diameter mesh screen (PG2).

*Data collected* – in each milling trial using whole pellets and the milled product, the data collected were identical to those obtained for the chips. Moreover, some specific properties of the pellets were also determined. These were the durability and fines rate (DU and F, measured according to EN 15210-1:2009 [32]), particle density (PD, measured according to EN 15150: 2011 [33]), bulk density (BD, measured according to EN 15103: 2009 [34]) and the median of the pellet ingredient particle size distribution (this property was determined using the disintegration and screening method recommended by Jensen et al. [35]).

*Parameters calculated* – the parameter used to link grinding energy consumption and particle size distribution difference between feed and products was that determined by the wood chip experiments. In this case the feed particle size distribution was characterised by the median of the pellet ingredient particle size distribution.

## 3. Results and discussion

### 3.1. Grinding energy

Table 4 shows the minimum and maximum energy consumption values when grinding wood chips and pellets. These data are of the same order of magnitude as those found in the literature (cf. Table 1), for similar wood species and moisture content levels. If all treatments are considered, it appears first of all that energy consumption varies greatly within a species, more than between species. Yet, the sample variability appears difficult to be in question as all necessary precautions have been taken in order limit to the minimum the variability between subsamples (homogeneous wood from sawmill and

**Table 3 – Characteristics of wood pellets used in the grinding trials. *H*1, average of moisture content class 1; *H*2, average of moisture content class 2; *n*, number of observations in the moisture content classes; DU, durability; PD, particle density at moisture content *H*2; BD, bulk density at moisture content *H*2; PIPSD Q50, median of particle size distribution of pellet ingredients.**

| | *H*1 (*n*) | *H*2 (*n*) | DU (%) | *F* (%) | PD (g/cm$^3$) | BD (kg/m$^3$) | PIPSD Q50 (mm) |
|---|---|---|---|---|---|---|---|
| Pellets 1 | 0.3 (16) | 12.0 (16) | 98.2 | 0.5 | 1.26 | 646 | 0.708 |
| Pellets 2 | 1.1 (16) | 7.7 (16) | 98.8 | 0.3 | 1.33 | 693 | 0.761 |
| Pellets 3 | 0.6 (16) | 9.2 (16) | 98.9 | 0.6 | 1.27 | 656 | 0.755 |
| Pellets 4 | 0.7 (16) | 5.9 (16) | 98.5 | 4.8 | 1.31 | 701 | 0.848 |
| Pellets 5 | 0.2 (15) | 7.1 (16) | 99.3 | 0.3 | 1.31 | 689 | 0.756 |
| Min | 0.2 | 5.9 | 98.2 | 0.3 | 1.26 | 646 | 0.708 |
| Max | 1.1 | 12.0 | 99.3 | 4.88 | 1.33 | 701 | 0.848 |

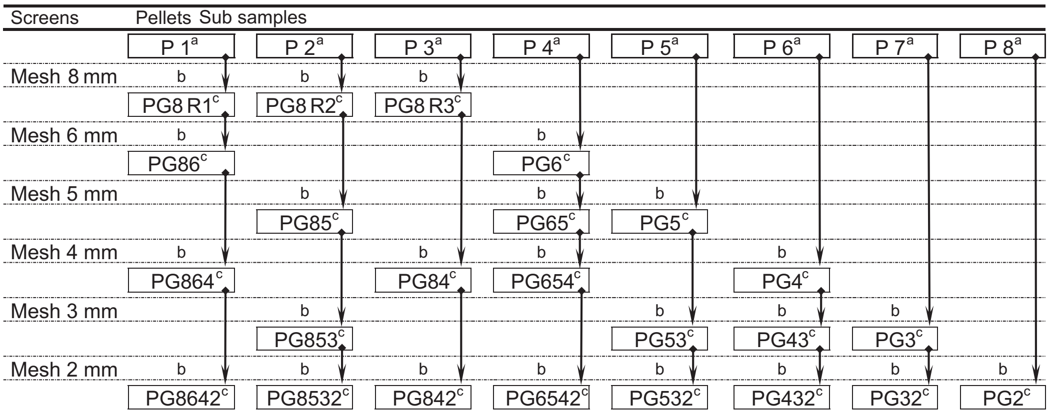


**Fig. 3 – Pellets milling experimental plan applied to both moisture content class and pellets combinations: (a) mass, moisture content and internal particle size distribution determination, (b) energy recording for milling the feed into the product, (c) mass, moisture content and particle size distribution determination.**

sample division using riffle divider). The following consumption data were recorded: for beech, 5.1–307.0 Wh/kg, for oak:6.2–172.2 Wh/kg, for pine:4.9–199.2 Wh/kg and for spruce 5.4–251.9 Wh/kg. The energy consumption data recorded during pellet grinding spanned a smaller range, lying between 1.4 and 18.2 Wh/kg for the five types of pellets tested. Next, the moisture content clearly affects the energy consumption when grinding chips: the higher the moisture content, the more the energy consumption increases and the greater the differences between min and max. Pellets by their nature have a smaller moisture content range than chips. Nonetheless, this parameter also appears relevant to this product, with the highest energy consumption levels systematically being recorded for the highest moisture content classes.

However, within the moisture content classes there were considerable differences between the minimum and maximum consumption levels noted. Lastly, for similar moisture content levels, grinding pellets used less energy than grinding chips. The differences between minimum and maximum noted were also smaller.

### 3.2. *Chips*

For the species tested and the moisture content classes defined, the middle columns of Table 5 (columns $C$, $n$ and $DSS_{min}$) show pairs $C$ and $n$ which minimise the DSS between the measured values and those obtained by using $C$ and $n$ in Charles' relation (4). It appears that the constant $C$ tends to increase with the moisture content of the material, whereas the exponent $n$ tends to decrease. These opposing tendencies make it hard to interpret the actual effects of moisture content and species on these materials' energy consumption during grinding. Therefore, as an initial approximation, for purposes of comparison, the materials can usefully be characterised by a single parameter (constant), at the expense of a slight loss of accuracy. The average of the exponents $n$, for all species and moisture content levels together, is 2.1. Used in Charles' relation (Eq. (4)) this value is closer to the exponent $n$ leading to Von Rittinger's relation ($n = 2$) than that of Kick ($n = 1$) or Bond ($n = 1.5$). Von Rittinger's relation (Eq. (1)) is therefore suggested for the purpose of characterising grinding of the

**Table 4 – Energy consumption for grinding wood chips and pellets: minima and maxima recorded for different material moisture content classes, for all feed and product particle size distributions ($H$, moisture content in %; E Min and E Max in Wh/kg, minimum and maximum grinding energy consumption for the material and moisture content class concerned). Bold type: minimum and maximum values for chips and pellets.**

| Moisture content | $0 < H < 4.99$ | | $5 < H < 9.99$ | | $10 < H < 14.99$ | | $15 < H < 19.99$ | | $20 < H < 24.99$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| Material | E Min | E Max | E Min | E Max | E Min | E Max | E Min | E Max | E Min | E Max |
| Beech | 5.1 | 59.9 | 7.4 | 75.7 | 11.9 | 135.1 | 21.7 | 249.2 | 28.3 | **307.0** |
| Oak | 6.2 | 50.1 | 13.4 | 107.7 | 21.2 | 172.3 | 21.1 | 113.8 | 24.6 | 170.2 |
| Pine | **4.9** | 40.7 | 5.1 | 61.2 | 13.5 | 111.6 | 19.6 | 195.7 | 31.5 | 199.2 |
| Spruce | 5.4 | 54.6 | 7.9 | 162.6 | 14.3 | 244.0 | 15.3 | 240.3 | 17.3 | 251.9 |
| Pellets 1 | 1.9 | 9.3 | – | – | 2.6 | 16.1 | – | – | – | – |
| Pellets 2 | 2.2 | 9.4 | 3.0 | **18.2** | – | – | – | – | – | – |
| Pellets 3 | 1.5 | 8.2 | 2.0 | 12.9 | – | – | – | – | – | – |
| Pellets 4 | 1.6 | 8.3 | 1.9 | 13.0 | – | – | – | – | – | – |
| Pellets 5 | **1.4** | 7.6 | 1.6 | 11.5 | – | – | – | – | – | – |

**Table 5 – C and n pair minimising DSS, using Charles' relation and $C_{VR}$ minimising DSS using Von Rittinger's relation. N, number of observations; MC, average moisture content of class (%); C, constant of Charles' relation; n, exponent of Charles' relation; DSSmin, sum of minimum deviations obtained with C and n; $C_{VR}$, von Rittinger's constant; $n_{VR}$, exponent leading to von Rittinger's relation; $DSS_{VR}$, least squares obtained with $C_{VR}$ and $n_{VR}$.**

| Species | N | MC | C | $n$ | $DSS_{min}$ | $C_{VR}$ | $n_{VR}$ | $DSS_{VR\ min}$ |
|---|---|---|---|---|---|---|---|---|
| Spruce | 12 | 1.5 | 11.3 | 2.7 | 47.8 | 23.7 | 2.0 | 157.0 |
| Spruce | 13 | 7.0 | 20.8 | 2.9 | 255.9 | 43.8 | 2.0 | 552.8 |
| Spruce | 16 | 12.2 | 73.1 | 2.4 | 588.9 | 105.2 | 2.0 | 1138.3 |
| Spruce | 13 | 16.1 | 156.6 | 2.2 | 1534.9 | 185.5 | 2.0 | 1931.9 |
| Spruce | 8 | 21.3 | 467.5 | 1.5 | 1346.0 | 291.5 | 2.0 | 2920.4 |
| Pine | 13 | 4.9 | 21.9 | 2.3 | 182.9 | 31.8 | 2.0 | 247.5 |
| Pine | 13 | 9.0 | 36.9 | 2.4 | 354.2 | 55.5 | 2.0 | 527.1 |
| Pine | 15 | 13.5 | 87.4 | 2.4 | 1799.8 | 126.3 | 2.0 | 2540.9 |
| Pine | 16 | 17.4 | 185.7 | 2.0 | 2189.2 | 188.1 | 2.0 | 2191.7 |
| Pine | 5 | 20.8 | 249.6 | 1.8 | 858.1 | 204.5 | 2.0 | 1158.0 |
| Beech | 13 | 1.1 | 15.6 | 2.3 | 164.7 | 21.8 | 2.0 | 197.3 |
| Beech | 13 | 8.1 | 65.7 | 1.9 | 321.9 | 55.2 | 2.0 | 375.9 |
| Beech | 13 | 13.4 | 178.8 | 1.5 | 958.6 | 86.5 | 2.0 | 3155.3 |
| Beech | 11 | 16.5 | 141.0 | 1.6 | 565.9 | 77.3 | 2.0 | 1398.1 |
| Beech | 13 | 21.7 | 171.3 | 1.6 | 1056.4 | 99.2 | 2.0 | 2433.5 |
| Oak | 13 | 1.4 | 12.9 | 2.9 | 72.5 | 32.0 | 2.0 | 389.7 |
| Oak | 15 | 7.8 | 55.0 | 2.5 | 1882.3 | 94.7 | 2.0 | 3077.9 |
| Oak | 14 | 12.4 | 130.6 | 2.0 | 1680.7 | 129.3 | 2.0 | 1681.4 |
| Oak | 12 | 17.0 | 184.8 | 1.8 | 1719.7 | 143.6 | 2.0 | 2195.3 |
| Oak | 9 | 22.4 | 187.0 | 1.9 | 1218.3 | 168.2 | 2.0 | 1301.6 |
| Total | 250 | | Mean | 2.1 | | | | |

species considered. The right-hand columns of Table 5 (columns $C_{VR}$, $n_{VR}$ and $DSS_{VRmin}$) show the values of the constant $C_{VR}$ that minimise the DSS between measured values and those estimated with the aid of Von Rittinger's relation. Each species, at a particular moisture content level, is therefore characterised by a single constant.

The relation between the index expressing the particle size reduction in Von Rittinger's relation ($1/x_2 - 1/x_1$) and the grinding energy consumption is illustrated in Figs. 4–7 for the materials tested.

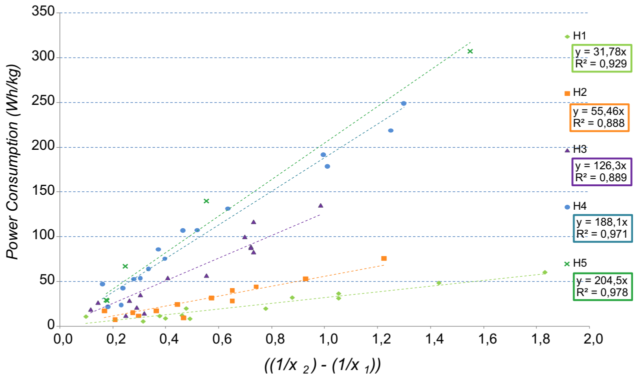


**Fig. 5 – Pine, grinding energy consumption, for five moisture content levels increasing from H1 to H5, x1 and x2: feed and product particle size distribution median, respectively.**

Thus expressed, the grinding energy consumption, for the four species concerned, shows two common trends. Firstly, within each moisture content level, energy consumption is proportional to Von Rittinger's particle size reduction factor. The quality of the proportionality relations between these variables is characterised by high determination factors ($R^2$ between 0.82 and 0.98). Von Rittinger's relation therefore largely explains the energy consumption differences within the moisture content classes for each species: the greater the difference in particle size distribution between the feed and the product, the more energy is required for grinding. In accordance with Von Rittinger, a particular species at a particular moisture content level can be considered a material, irrespective of the other moisture content levels, and characterised by a specific constant ($C_{VR}$).

Secondly, energy consumption rises as a function of the grinder feed moisture content level. For each species Fig. 8 shows the constants $C_{VR}$, characterising the moisture content classes, on the y-axis of the average moisture content of the class concerned. It appears that Von Rittinger's constant is proportional to the moisture content ($H$) of the material, according to a relation characteristic of the species. For each

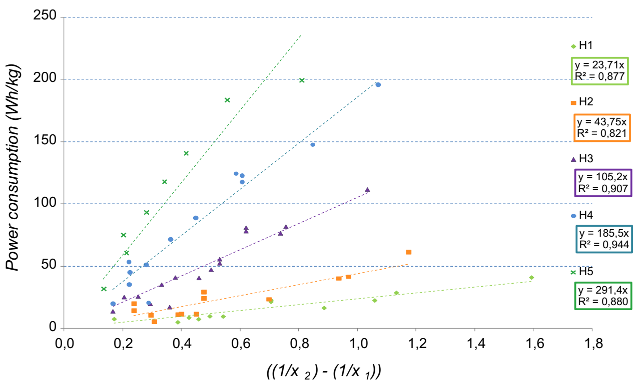


**Fig. 4 – Spruce, grinding energy consumption, for five moisture content levels increasing from H1 to H5, x1 and x2: feed and product particle size distribution median, respectively.**

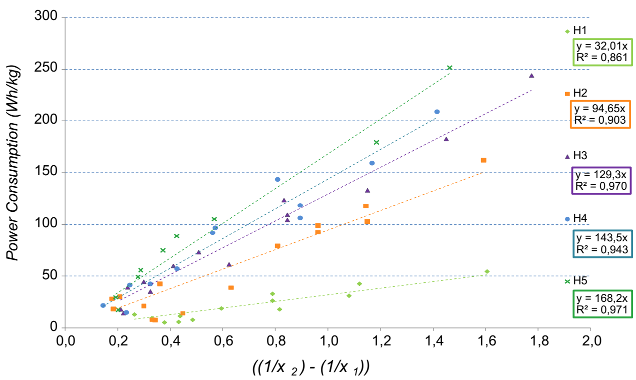


**Fig. 6 – Oak, grinding energy consumption, for five moisture content levels increasing from H1 to H5, x1 and x2: feed and product particle size distribution median, respectively.**

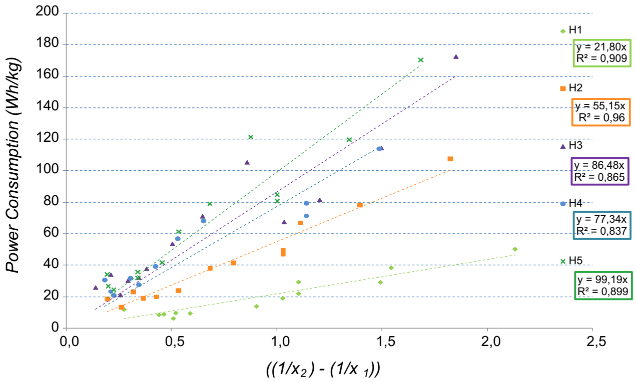


**Fig. 7 – Beech, grinding energy consumption, for five moisture content levels increasing from H1 to H5, *x1* and *x2*: feed and product particle size distribution median, respectively.**

species, the relations identified have high determination factors (between 0.74 and 0.93). If $M$ is defined as a constant characteristic of the species, such that $C_{VR} = M \times H$, and that relation is introduced into Eq. (1), the specific grinding energy can be expressed by Eq. (6).

$$E_{1-2} = MH\left(\frac{1}{x_2} - \frac{1}{x_1}\right) \qquad (6)$$

Factor $M$ characterises the grindability of a species with the aid of a single constant, the moisture content and the particle size distribution characteristics of the feed and the product. The values are beech, $M = 5.11$; oak, $M = 8.54$; pine, $M = 9.65$; and spruce, $M = 11.85$.The unit associated with the constant $M$ balances the units of the equation when the $x$ are expressed in mm, mass in kg, moisture content in % and energy consumption in Wh/kg dry matter. The quality of the model using the parameter $M$ could be improved and in fact, more complex models would lead to a better fit. For example, the middle columns of Table 5 show that using a variable pair of parameters C and n results in a lower DSS than is the case when parameter n is fixed to obtain Von Rittinger's relation. However, these relations are less general and are characteristic of a material and its moisture content. In practice, these specific relations will be researched in order to characterise a plant's grinding energy consumption and deduce the expected impact of altering the feed or product particle size distribution.

The proposed method still has to be confirmed using mills with different principles and scales to that used in this experiment and with different species and biomasses. At this stage, Eq. (6) takes into account the influence of moisture content and particle size distribution on the milling energy requirements, as it was already observed by Mani [15] and Esteban [18]. Further, parameter $M$ may perhaps be linked to other physical properties of the wood, such as the particle density or resilience, but it already has the advantage of characterising grindability by a single value. It also allows the effects of altering the feed moisture content, the particle size distribution, or both of these parameters on grinding energy consumption to be estimated. Lastly, it provides an initial guide to dimensioning a grinding plant's energy requirements.

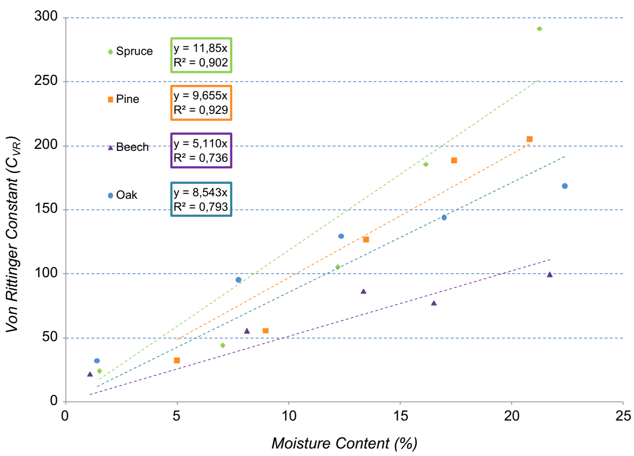


**Fig. 8 – Trend of Von Rittinger's constant as a function of moisture content for four species of wood (*H*: moisture content on moist base in % and $C_{VR}$, Von Rittinger's constant).**

### 3.3. *Pellets*

For the five types of pellets examined in this study, Fig. 9 shows the difference between the energy consumption when grinding whole pellets and when grinding pellets that had been pre-milled using a larger diameter mesh screen (8–3 mm according the milling position in the experimental planning). On average, grinding the pellets in question consumes 1.8 Wh/kg, 2.0 Wh/kg, 2.1 Wh/kg, 3.7 Wh/kg, 5.3 Wh/kg and 11.4 Wh/kg using screens with 8 mm, 6 mm, 5 mm, 4 mm, 3 mm and 2 mm mesh, respectively. On average, the same pellets previously ground using a screen with a larger diameter mesh than that used for the measurement had energy consumption values of 0.9 Wh/kg, 1.1 Wh/kg, 2.1 Wh/kg, 3.2 Wh/kg and 7.6 Wh/kg, using screen with 6 mm, 5 mm, 4 mm, 3 mm and 2 mm mesh sizes, respectively. The logical conclusion is therefore that, for the screen mesh diameters in question, milling whole pellets systematically consumes more energy than is the case with pre-milled pellets.

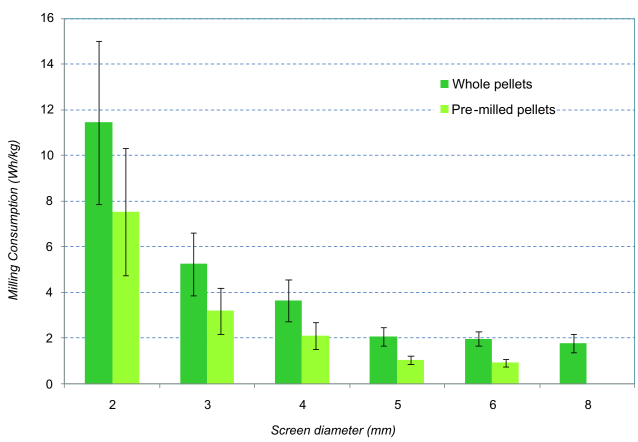


**Fig. 9 – Energy consumption when milling pellets and their component material on 2–8 mm diameter mesh screens.**

It is to be noted that, for the grinding passes using screens of mesh diameter 5 mm, 6 mm and 8 mm the recorded energy consumption was stable irrespective of the screen concerned. Moreover, the levels were low, in the order of 2 Wh/kg, compared with the values when grinding biomass that had not been pre-densified (cf. Section 3.1) and also compared with grinding pellets using screens of smaller mesh diameter (2 mm, 3 mm and 4 mm).It is therefore assumed that grinding on these screens breaks down the pellet structure but only reduces the pellet ingredient particle sizes by a negligible amount.

When milling pellets using 2 mm, 3 mm and 4 mm mesh screens the average energy consumption for whole pellets and pre-milled pellets rose as the mesh diameter decreased. Moreover, the measurement variability and the energy consumption difference between the two types of material increased similarly. It is therefore assumed that grinding pellets on 2 mm, 3 mm and 4 mm diameter mesh screens not only breaks down the pellet structure but also reduces the ingredient particle sizes. It was not possible, for the pellets in question, to establish a relation between the energy needed to break down the structure and another property of the pellets (such as durability) and the latter is therefore considered to be stable for the various materials included in this study.

A model of energy consumption when milling pellets and their component material is therefore proposed in the form of Eq. (7). This model takes account of the energy needed to break down the pellet structure. The particle size reduction is expressed by Von Rittinger's parameter calculated on the basis of the particle size distribution medians of the grind ($x_2$) and the pellet ingredients to characterise the input material ($x_1$).

The model takes account of the energy needed to break down the pellets structure. This energy is to be determined for pellets and is considered as nil for pre-milled pellets. In a first step, the three parameters $a$, $b$ and $D_{en}$ pellets have been calculated to minimise the DSS between values supplied by the model and the actual measured consumption. The mean value of $D_{en}$ pellets has been calculated as having the value of 2.5 Wh/kg. In a second step parameters a and b have been recalculated to minimise the DSS between values supplied by the model and the actual measured consumption when the energy needed to break down the pellets is set at 2.5 Wh/kg.

$$E_{1-2} = \left[a\left(\frac{1}{x_2} - \frac{1}{x_1}\right) + b\right] + D_{En} \quad (7)$$

Table 6 provides parameters $a$ and $b$ for the afore described model. For each type of pellets, considered individually, at two moisture content levels, the relation between the two values is characterised by high $R^2$ levels (0.868–0.971). However, although the effect of moisture content has been shown (cf. Section 3.1) it has not been incorporated into the model, as was the case with wood chips. Moisture content appears to affect each type of pellet differently. That would need to be confirmed by increasing the number of moisture content levels of the pellets milled, something that is difficult to do in practice given this fuel's low moisture content range. A global model using parameters $a$ and $b$ determined individually for each type of pellet produces a relation characterised by an $R^2$ of 0.956.

Milling of pellets with different moisture content values can thus be modelled relatively accurately, on the basis that as well as the energy needed to mill the biomass, energy is also needed to break down the pellet structure. The milling energy for a particular type of pellets is then characterised by a pair of parameters ($a$ and $b$) characteristic of the pellet moisture content.

**Table 6 – Parameters $a$ and $b$ minimising the DSS between measured energy consumption and estimated energy consumption using the model, for five different pellets, each with two moisture content values.**

| Pellets | $H$ | $N$ | $D_{En}$ pellets | $a$ | $b$ | DSS | $R^2$ |
|---|---|---|---|---|---|---|---|
| 1 | 0.8 | 16 | 2.50 | 6.05 | 0.79 | 6.5 | 0.883 |
| 1 | 11.7 | 16 | 2.50 | 13.54 | 1.75 | 5.8 | 0.971 |
| 2 | 1.1 | 16 | 2.50 | 19.15 | −8.42 | 5.0 | 0.909 |
| 2 | 7.7 | 16 | 2.50 | 17.36 | −2.40 | 19.7 | 0.950 |
| 3 | 0.6 | 16 | 2.50 | 13.02 | −5.93 | 2.8 | 0.957 |
| 3 | 9.3 | 16 | 2.50 | 14.05 | −3.49 | 15.8 | 0.916 |
| 4 | 0.7 | 16 | 2.50 | 9.76 | −1.25 | 5.7 | 0.868 |
| 4 | 6.0 | 16 | 2.50 | 9.56 | −0.20 | 6.4 | 0.968 |
| 5 | 0.2 | 15 | 2.50 | 9.87 | −3.86 | 2.8 | 0.958 |
| 5 | 7.09 | 16 | 2.50 | 11.22 | −2.47 | 10.4 | 0.919 |
| All | | 159 | Selected according to pellets | | | 81.0 | 0.956 |

## 4. Conclusions

The following conclusions have been drawn from this study: for beech, oak, pine and spruce chips with maximum 22% moisture content, the energy needed to mill chips of these materials varies greatly and essentially depends on three factors, i.e. the material moisture content, the particle size difference between the feed and the product and the species of wood.

The study suggests that the Von Rittinger's parameter calculated using the feed and product particle size distribution medians is the most suited to expressing the energy consumed when milling wood chips in selected moisture regime. A high Von Rittinger's parameter indicates a higher consumption of energy for the milling. Moreover, this parameter is proportional to the material moisture content, i.e. increased moisture content increases the energy consumption for milling linear.

The methodology proposed in this paper enables wood chip grindability to be characterised by a single parameter, $M$. In the context of this study, $M = 5.11$ for beech, $M = 8.54$ for oak, $M = 9.65$ for pine and $M = 11.85$ for spruce. The unit associated with the constant $M$ balances the units of the equation when the $x$ are expressed in mm, mass in kg, moisture content in % and energy consumption in Wh/kg dry matter.

In practical wood milling operations, the here proposed model will be used to design milling facilities. Alternatively it may be used to estimate the possibility to process a new feed material (with different particle size distribution or moisture content) in an existing facility and anticipate the product output. Finally it offers the possibility to optimise the energy costs of solid biofuels supply chains, e.g. the interaction between milling and drying operations.

Concerning wood pellets, the energy needed to mill pellets is affected by the same factors as wood chip milling: moisture content, particle size difference between feed and product, and type of pellets milled. However, for comparable moisture content levels, and screens with equivalent mesh diameter, less energy is consumed when grinding pellets than chips.

When milling pellets using 5, 6 and 8 mm mesh diameter screens the energy consumption is stable around 2.0 Wh/kg, and is therefore of minor importance when planning and performing a milling operation.

For finer milling, using 2, 3 and 4 mm mesh diameter screens, the energy consumption and the energy consumption ranges increase. In this case, for each type of pellet a model can be proposed that expresses energy consumption for pellets and their component material on the basis of the pellet breakdown energy (estimated at 2.5 Wh/kg) and a Von Rittinger parameter. In practical pellets milling operations, the results suggest that the energy consumption increase dramatically when using screens with mesh diameter below 5.0 mm and this economical parameter should be considered when planning the milling operation.

## REFERENCES


[1] Ryckmans Y, Allard P, Liegeois B, Mewissen D. Conversion of a pulverized coal power plant to 100% wood pellets in Belgium. In: Proceedings of the second conference on Pellets, Jönköping, Sweden; 30 May–1 June 2006. p. 59–61.
[2] Demirbas A. Sustainable cofiring of biomass with coal. Energy Conversion and Management 2003;44:1465–79.
[3] Demirbas A. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion-related environmental issues. Progress in Energy and Combustion Science 2005;31:171–92.
[4] Baxter L. Biomass-coal co-combustion: opportunity for affordable renewable energy. Fuel 2005;84:1295–302.
[5] Nishiyama A, Shimojima H, Ishikawa A, Itaya Y, Kambara S, Moritomi H, et al. Fuel and emissions properties of Stirling engine operated with wood powder. Fuel 2007;86:2333–42.
[6] Paulrud S, Nilsson C. The effects of particle characteristics on emissions from burning wood fuel powder. Fuel 2004;83:813–21.
[7] Tmej C, Haselbacher H. Development of wood powder feeding into gas turbine combustion chambers. In: First world conference on biomass for energy and industry. Sevilla, Spain: James & James (Science Publishers); 5–9 June 2000. p. 783–6.
[8] Rhén C, Öhman M, Gref R, Wästerlund I. Effect of raw material composition on woody biomass pellets on combustion characteristics. Biomass and Bioenergy 2007;31:66–72.
[9] Esteban L, Mediavilla I, Fernandez M, Carrasco J. Influence of the size reduction of pine logging residues on the pelletizing process and on the physical properties of pellets obtained. Proceedings of the second conference on Pellets, Jönköping, Sweden; 30 May–1 June 2006.
[10] Masson A. Le broyage, première partie, nature de l'opération, état dimensionnel de la matière broyée, énergie nécessaire au broyage. Revue Universelle des Mines, 9e série, tome 1960;XVI(8):341–9.
[11] Charles RJ. Energy-size reduction relationships in comminution. Transactions of AIME, Mining Engineering 1957;208:80–8.
[12] Hukki RT. Proposal for a solomnic settlement between theories of von Rittinger. Kick and Bond. Transactions of AIME 1962:223.
[13] Morrell S. An alternative energy–size relationship to that proposed by Bond for the design and optimisation of grinding circuits. International Journal of Mineral Processing 2004;74:133–41.
[14] Stambioliadis ET. A contribution to the relationship of energy and particle size in the comminution of brittle particulate materials. Minerals Engineering 2002;15:707–13.
[15] Mani S, Tabil LG, Sokhansanj S. Grinding performance and physical properties of wheat and barley straw, corn stover and switchgrass. Biomass and Bioenergy 2004;27:339–52.
[16] Vigneault C, Rothwell TM, Bourgeois G. Hammer mill grinding rate and energy requirements for thin and conventional hammers. Canadian Agricultural Engineering 1992;34:203–6.
[17] Rothwell TH, Vigneault C, Southwell PH. Hammermill drill screen evaluation on an energy and economic basis. Canadian Agricultural Engineering 1992;34:315–9.
[18] Esteban LS, Carrasco JE. Evaluation of different strategies for pulverization of forest biomasses. Powder Technology 2006;166:139–51.
[19] Laskowski J, Lysiak G. Relationships between resistance characteristics of barley kernels and energy consumption during grinding on hammer mill. International Agrophysics 1997;11:265–71.
[20] Laskowski J, Lysiak G, Melcion JP. Cereal grain resistance analysis in the aspect of energy utilization in the process of disintegration. International Agrophysics 1998;12:205–8.
[21] Laskowski J, Lysiak G. Use of compression behaviour of legume seeds in view of impact grinding prediction. Powder technology 1999;105:83–8.
[22] Gil M, Arauzo I, Teruel E, Bartolomé C. Milling and handling *Cynara Cardunculus L.* for use as solid biofuel: experimental tests. Biomass and Bioenergy 2012;41:145–6.
[23] Bitra VSP, Womac AR, Chevanan N, Miu PI, Igathinathane C, Sokhansanj S, et al. Direct mechanical energy measures of hammer mill comminution of swithgrass, wheat straw, and corn stover and analysis of their particle size distribution. Powder Technology 2009;193:32–45.
[24] Arias B, Pevida C, Fermoso J, Plaza MG, Rubiera F, Pis JJ. Influence of torrefaction on the grindability and reactivity of woody biomass. Fuel Processing Technology 2007. http://dx.doi.org/10.1016/j.fuproc.2007.09.002.
[25] Bridgeman TG, Jones JM, Williams A, Waldron DJ. An investigation of the grindability of two torrefied energy crops. Fuel 2010;89:3911–8.
[26] Phanphanich M, Mani S. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. Bioresource Technology 2011;102:1246–53.
[27] Bergman PCA, Kiel JHA., Veringa HJ. Combined torrefaction and pelletisation, the TOP process. Study report, ECN biomass, ref ECN-C-05-073; 2005.
[28] Miao Z, Grift TE, Hansen AC, Ting KC. Energy requirement for comminution of biomass in relation to particle physical properties. Industrial Crops and Products 2011;33:504–13.
[29] CEN/TS 15149-1:2010, Solid biofuels – method for the determination of particle size distribution – part 1: oscillating screen method using sieve aperture of 3.15 mm and above.
[30] CEN/TS 15149-2:2010, Solid biofuels – method for the determination of particle size distribution – part 2: vibrating screen method using sieve aperture of 3.15 mm and below.
[31] EN 14774-2:2009, Solid biofuels – methods for determination of moisture content – oven dry method – part 2: total moisture – simplified method.
[32] EN 15210-1:2009, Solid biofuels – methods for the determination of mechanical durability of pellets and briquettes – part 1: pellets.
[33] EN 15150:2005, Solid biofuels – methods for the determination of particle density.
[34] EN 15103:2009, Solid biofuels – methods for the determination of bulk density.
[35] Daugbjerg Jensen P, Temmerman M, Westborg S. Internal particle size distribution of biofuels pellets. Fuel 2011;90:980–6.