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# Hammer mill operating and biomass physical conditions effects on particle size distribution of solid pulverized biofuels

Miguel Gil *, Inmaculada Arauzo

*Centre of Research for Energy Resources and Consumptions, University of Zaragoza, Mariano Esquillor 15, E-50018 Zaragoza, Spain*

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ABSTRACT

Milling is a required pre-treatment for the use of biomass as a pulverized solid biofuel in some thermochemical technologies such as combustion, gasification and bioethanol production, as well as in densification processes. The particle size plays a key role on these energy conversion technologies. Experimental tests for poplar and corn stover were performed to obtain pulverized material at different physical conditions of the biomass (input particle size and moisture content) and operational parameters (opening sizes of the screen and angular speed of hammers). Fourteen parameters related to size central trends, dispersion and shape of particle size distribution (PSD) were calculated and analyzed by a novel data post-processing methodology, combining Artificial Neural Networks and statistical analysis. Results show that the characteristic size of the product (geometric mean size) is mainly influenced by the classification of the screen with values from five to eight times lower than their openings size. The angular speed of the hammer governs the variability and dispersion of sizes. The higher the angular speed, the lower the dispersion on particle size. Physical conditions of the biomass present a negligible effect on PSD.

## 1. Introduction

The European Commission established the “20-20-20” targets in order to achieve in 2020 a greenhouse gas emission reduction by 20%, a renewable energy contribution of 20% on the final energy consumption and an increase of the energy efficiency by the 20% [1]. In this context, biomass should play a key role due to its huge potential for substitution of fossil fuels with significant reduction of carbon dioxide emissions assessed between 55% to 98% [1]. However some economic, social and policy barriers must be overcome.

Regarding biomass, energy conversion technologies based on pulverized/powdered materials present important advantages such as a higher area/volume ratio (specific surface area), improving the energy conversion efficiency and the material behavior on handling labors. However, fine grinding is energy intensive and a balance needs to be struck between this cost and efficiency improvement. Research efforts are required around the requirements of the particle size of milled biomass:

- A methodology to characterize the particle size and shape in depth
- Improvements on the characterization and control of milling process to reduce the energy consumption and to obtain particles with the desirable sizes.
- An accuracy description of the size requirements imposed by each final user

With regard to goal 1, the studies on the characterization of the biomass particle morphology have been traditionally scarce. However, the high diversity on shape and on size (from few microns to the highest imposed size limit) due to the breakage process itself deserves a higher effort in its description. In this sense, a few researchers [2–6] focused on obtaining not only the particle size by standard procedure but also the effects of non-sphericity on the description of biomass particle morphology.

Most milling reports are focused on goal 2. In this regard, authors focused on the influence of several operational variables and the kind of biomass on milling energy consumption and the size distribution of the milled product. Himmel et al. [7] tested poplar, wheat straw and corn stover with hammer- and knife mill, varying the rejection screen size, the feed rate and the underpressure on the mill discharge. Mani et al. [8] and Bitra et al. [9] tested switchgrass, corn stover and wheat straw with hammer mill at several operational conditions. In addition, [9] also studied the knife mill varying the rejection screen size from 12.7 to 50.8 mm, the feed rate from 120 to 660 kg $h^{-1}$ and the operating speed from 250 to 500 rpm [10–12].Gil et al. [13] showed also the influences of input biomass conditions of poplar and corn stover and operating factors on milling energy consumption, on the drying effect of biomass during milling and on other handling behavior indicators such as bulk density and angle of repose of the ground particles.

Finally and related to goal 3, multiple researchers focused on determining the size requirements and effects of pulverized biomass not only on the handling properties but also on the efficiency of mass and heat transfer in combustion, gasification and bioethanol production. In

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* Corresponding author. Tel.: +34 976 761863; fax: +34 976 732078.
*E-mail addresses:* miguelgc@unizar.es (M. Gil), iarauzo@unizar.es (I. Arauzo).

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**Nomenclature**

| | |
|---|---|
| $C_g$ | coefficient of gradation |
| $C_u$ | uniformity coefficient |
| $d_{gm}$ | geometric mean diameter (mm) |
| $d_p$ | particle diameter (mm) |
| $d_{target}$ | maximum particle size of obtained product from milling process (mm) |
| $d_{10}$ | effective size (mm) |
| $d_{50}$ | median diameter (mm) |
| $HS_{gm}$ | high graphic geometric standard deviation |
| $h_i$ | input moisture content |
| $I_S$ | input particle size (mm) |
| $l_{RR}$ | Rosin–Rammler size parameter (mm) |
| $I_u$ | uniformity index |
| $K_g$ | geometric kurtosis |
| $l_{RR}$ | Rosin–Rammler size parameter |
| $LS_{gm}$ | low graphic geometric standard deviation |
| $MR_s$ | mass relative span |
| $m_{RR}$ | Rosin–Rammler distribution parameter |
| $rev$ | experimental variable under analysis: angular speed |
| $S_{gm}$ | geometric standard deviation |
| $Sk_g$ | geometric skewness |

*Acronyms*

| | |
|---|---|
| ANN | Artificial Neural Network |
| CCD | central composite design |
| PSD | particle size distribution |
| RSM | response surface methodology |
| RR | Rosin–Rammler distribution |
| SRF | short rotation forestry |

combustion processes, the optimal size is established according to several criterions such as the residence time [14–16]; the thermodynamic conversion of the particle inside the combustion camera (e.g. Lu et al. [17] showed a volatile yields decreasing with an increasing particle size and Sudhakar and Kolar [18] found the strongest influence of size on devolatilization time for wood particle); the flame stability (very fine particles, $d_p < 0.1$ mm, plays a key role on the stability of the flame in pulverized wood burners [19,20]); and the chemical composition itself (Bridgeman et al. [21] reported that the fine fractions have a significantly higher concentration of inorganic matter, moisture and nitrogen content but lower carbon content and calorific value than larger particles for switchgrass and reed canary). Similar effects can be observed in gasification processes [22,23]. Regarding bioethanol production, a decreasing of particle size involves higher hydrolysis yields of the lignocellulose [24, 25], but a depth size characterization is required because some studies [26] show that a size reduction further than 0.4 mm has little effect on hydrolysis rates.

Other authors focused their works on the effects of particle size on handling behavior of milled biomass. Ileleji and Zhou [27] observed a better flow behavior of corn stover at lower particle size by means of angle of repose tests. Paulrud et al. [2] found that tendency to bridge was a combined effect between particle size and shape for wood powder ($d_p < 2.25$ mm). Gil et al. [28] also observed this tendency for three kinds of milled cardoon at different particle size ($d_p < 0.5$–5 mm), and later reported the underlying mechanism that govern the handling behavior for poplar and corn stover ($d_p < 5$ mm), partially, due to effects of particle size and shape [29].

The aim of this study is to find the influence of the biomass conditions (moisture content and size at mill inlet) and the mill operational variables (opening size of output screen and angular speed of the hammers) on the final particle size in order to establish the conditions of milling process to obtain the desired final particle size.

## 2. Materials and methods

### 2.1. Biomass products

Two biomass resources were tested: SRF poplar and corn stover. They differ in their cultivation goals (forestry energy crop vs residue of agricultural crop), the kind of resource (woody vs herbaceous) as well as in their chemical compositions and physical properties. However, both resources present one of the highest potential for biofuels due to the high yields of production of poplar as short rotation energy crop and the abundance of corn stover, one of the most widespread residues worldwide.

Tested SRF poplar (*Populus* spp.) was cultivated in Fuente Vaqueros (UTM coordinates: 30 N 431306 4118679), province of Granada, south of Spain and corn plant (*Zea Mays* L.) was cultivated in Sariñena (UTM coordinates: 30 N, 738030 4629314) province of Zaragoza, northeast of Spain. Each resource was divided into four fractions. Each fraction was chipped and dried under different operational conditions, obtaining material at coarse-wet, coarse-dry, fine-wet and fine-dry conditions. Raw materials at different conditions of input particle size and moisture content allow evaluating their effects on milling process. A complete description about the physical conditions of each biomass fraction has been reported on Gil et al. [13].

### 2.2. Sample analysis

Standard specifications for sampling method (CEN/TS 14778–1:2005 EX [30]), moisture content (CEN/TS 14774–1:2004 [31]) and particle size analysis (CEN/TS 15149–2:2006 [32]) were used. Sieves (under standard ISO 3310–1:2000 [33]) with apertures of (0.1, 0.25, 0.5, 1, 2 and 5) mm were assembled on a vibrating screen machine (Orto Arlesa, vibro model). Milled materials were screened for 20 min. Sieving time was established in the pre-test to guarantee that any mass changes of the size fractions must be below 0.3% $\min^{-1}$ (CEN/TS 15149–2:2006 [32]) related to the total sample mass.

For the particle size analysis, probability density function and cumulative distribution function were calculated. Fourteen parameters from both distributions are obtained to get a complete characterization of particle size distribution (PSD). Geometric method for mean diameter ($d_{gm}$), standard deviation ($S_{gm}$), skewness ($Sk_g$) and kurtosis ($K_g$) are calculated according to Folk and Ward formulation [34]. Rosin and Rammler function [35] fit the cumulative distribution function with $R^2$ values around 99% (Section 3.5). $F(d_p)$ is the cumulative undersize percentage, $m_{RR}$ is the distribution parameter and $l_{RR}$, the size parameter:

$$F\left(d_p\right) = 1 - exp\left(-\left(d_p / l_{RR}\right)^{m_{RR}}\right). \tag{1}$$

Rosin–Rammler distribution is used to obtain the required size percentiles ($d_x$) to calculate the rest of parameters to characterize particle size distributions: mean diameter ($d_{50}$), effective size ($d_{10}$), high and low graphic geometric deviation ($HS_{gm} = d_{84} / d_{50}$; $LS_{gm} = d_{50} / d_{16}$), mass relative span ($MR_S = (d_{90} - d_{10}) / d_{50}$), uniformity index ($I_u = d_{95} / d_5$), uniformity coefficient ($C_u = d_{60} / d_{10}$) and coefficient of gradation ($C_g = {d_{30}}^2 / (d_{60} - d_{10})$).

### 2.3. Data post-processing strategy: Artificial Neural Network and statistical analysis

Artificial Neural Networks (ANN) are very useful mathematical structures for characterizing and predicting complex problems in which multiple variables and their interactions play relevant role on final results. Taking into account that it is not suitable to perform