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Population balance model for biomass milling

Miguel Gil [a,*], Ennio Luciano [b], Inmaculada Arauzo [a]

[a] Research Centre for Energy Resources and Consumption (CIRCE), Universidad de Zaragoza, CIRCE Building, Campus Río Ebro, Mariano Esquillor Gómez, 15, 50018 Zaragoza, Spain
[b] Department of Mechanical Engineering, University of Zaragoza, Mara de Luna, E-50018 Zaragoza, Spain

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A B S T R A C T

The aim of this work is to develop a model of the milling process of biomass. For this purpose, a classic approach is selected. The breakage probability, characterized by a material mastercurve, and breakage function are used to determine the breakage matrix. A classification function is also proposed, based on physics of the process itself and the calculation of the impact number for a particle. Knowing all these, the milling product characteristic in the steady state can be reproduced. The model has been tested for the milling of two biomasses: an herbaceous one (corn stalk/leaves) and a woody biomass (poplar) in a commercial laboratory mill. The model will reproduce quite reasonably to both cumulative and discrete particle size distributions for the two biomasses tested and for several operating conditions of the mill (rotor speed, sieve openings and feed rate), as shown validating the model results with experimental work. Other parameters as input size of the material show to be less important for the sizes essayed. The main novelty of this work is to present this milling model for biomass material, introducing also the classification system modeling and the calculation of the number of impact.

1. Introduction

The use of biofuel has been increasing in the last years as alternative to fossil fuels in order to decrease the greenhouse gas emissions, mainly carbon dioxide. The rationale is that the photosynthesis of growing plants removes CO_2 from the atmosphere and subsequently eliminates its net contribution to the atmospheric build-up after combustion. Biomass utilization for bio-energy, bio-fuels or bio-based products requires the reduction of its size in order to make its energy conversion feasible and efficient. Intermediate size reduction i.e. chunking, chipping or shredding is widely required, nevertheless some well-known technologies like pulverized burners, co-firing with coal in power station, pellet or briquette production for domestic or industrial boilers or some ethanol production technologies require an extra intensive size reduction by means of the milling processes. The overall goal of a grinding process is the production of a well-defined product with a reasonable cost. For biomass resources, the high cost of this process is one of the main drawbacks for the development of renewable energy technologies based on pulverized biomass.

Industrial milling process involves multi-physics underlying mechanisms related to mechanics of contact and fracture, surface physics, fluidodynamics and, even possible thermal effects on materials. All of them are mixed in an intricate manner, still nowadays, incomplete and lack of physical understanding. Comminution process is related to material properties and to the design and operation variables of the mill, as well as all interactions between them. In all cases, material behavior must be known to understand the particle response under high velocity impacts (hammer mills). Other mechanisms, still uncharacterized, play relevant roles on milling process: the fluidodynamics of air-particle inside the mill chamber, the random particle-to-particle collisions and, above all, the size classification mechanism of the particle.

This process has been studied at several scales from the molecular level (e.g. crack growing) to industrial field [1] (e.g. grinding circuit including feeder, mills and classifiers). The last one has been focused on developing semi-empirical theories based on energy-size relationships and on experimental test campaign to determine the effects and influences of material conditions and operational variables on specific energy consumption and on the quality of the milled product.

Semi-empirical milling theories such as Rittinger [2], Kick [3], Walker [4], Bond [5], Hukki [6], or Morrell [7] developed several mathematical relationships taking into account the energy consumption involved in the particle size reduction between known input and output particle sizes. These theories have been a widespread use for brittle materials, such as glass and minerals. However, little work has been done with biomass resources. To our knowledge, only Temmerman et al. [8] adapted the Von Rittinger theory for biomass materials, specifically for wood chips and pellets.

Other authors focused their experimental campaign in obtaining the milling energy consumption and product quality for different herbaceous [9–13] and forest biomasses [11,13–15], testing several mill designs [10,14,16–18] or combinations between mills and different classifiers [15,19].

* Corresponding author. Tel.: +34 976 762954; fax: +34 976 732278.
E-mail addresses: miguelgc@unizar.es (M. Gil), eluciano@unizar.es (E. Luciano), iarauzo@unizar.es (I. Arauzo).

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No relationships have been found between general laws for particle properties relevant to grinding and first principles up to the present. Conceptually, mean particle properties or methods of probabilistic breakage mechanics have to be employed [1]. Population balance models (PBM) and discrete element models (DEM) are based on this theoretical concept. Material breakage behavior is characterized by its statistical probability of particle fracture (breakage probability, S) and the size description of the new progeny of particles generated after fracture (breakage function, B). A wide experience on the characterization of breakage behavior, mainly in mineral materials, can be reviewed in scientific literature [20–31]. However, under our knowledge, only one publication reported data with biomass resources [32].

Population balance models for milling processes have been widely developed, mainly, for mineral applications from 1970s. Austin [33] performed a PBM of high speed hammer mill for limestone, incorporating also particle damage accumulation after multi-impact. Nikolov [34,35] predicted the size distribution of the product from impact crushers through a PBM, analyzing the influence of rotor velocity and feed rate, and finally, Toneva, P. and Peukert, W. [36] reported a complete review of experiences and models. Further developments on PBM are heading to the integration of this kind of particle balances into computer simulations. The advances on computational power and techniques allow one to include in these models the multi-physics events (fracture, fluidodynamics, particle fatigue, random collisions …) that can mean a great step in comminution modeling and can be the most useful and promising tool for milling models [37]. In this sense, Djordjevic et al. [38] simulated both vertical and horizontal shaft impact crushers by DEM in order to determine the effects of design and operational conditions on energy collisions and on the particle breakage behavior. Gommeren et al. [39] developed a simulation of a dynamic model of the closed loop grinding to predict particle size distribution of the product. It was validated with PSD experimental data in order to be implemented in the control system as the next step. However, traditional materials like minerals and ores have been under study, and no experiences with biomass materials have been reported. Biomass presents two important drawbacks in comparison to mineral materials that increase the complexity of the process: non-brittle fibrous behavior [40,41] and non-spherical particle shape [14,42,43].

In this work, a population balance model of a lab-scale impact mill is carried out with two biomass resources: poplar and corn stalk/leaves. Breakage probability (S) and breakage function (B) of the material have been incorporated as well as a novel formulation of the particle classification related to the metal screen surrounding the mill chamber has been developed. Section 2 reports the model details, Section 3 describes the biomass and the experimental procedure and Section 4 shows the model validation with the experimental data.

Nomenclature

B	breakage function
$\underline{\underline{C}}$	classification matrix
d_p	particle size (mm)
DEM	Discrete Element Model
$\underline{f}$	feed material vector
f_{Mat}	resistance against the external load ($kgJ^{-1}m^{-1}$)
x	input particle size (mm)
k	number of impacts
$\underline{h}$	mixture of particle inside mill chamber previous to impact
$\underline{m}$	impacted material vector
$\underline{p}$	final product vector
PBM	population balance model
PSD	particle size distribution
$\underline{r}$	recirculated material vector
rev	angular speed of the mill rotor (rpm)
S	breakage probability
$W_{m,kin}$	impact energy (Jkg^{-1})
$W_{m,min}$	energy threshold for particle fracture (Jkg^{-1})
$\underline{\underline{X}}$	breakage matrix

2. Population balance model

Population balance model (PBM) predicts the particle size distribution of the milled product as a function of the material properties, the design and operational variables of the mill and the interactions between material and mill. It will contribute to understand the underlying mechanism that governs the milling in order to obtain a high quality product with the lowest feasible energy cost.

PBM is conceptually understood as a discrete mathematical method of particle flow balance of new daughter particles generated from the fracture of the mother ones. Fig. 1 shows a scheme of the flows involved in an impact mill with size classification. Particle flows are represented by vectors whose components show their particle size distribution divided into eight discrete size ranges: 0, 0.045, 0.1, 0.15, 0.25, 0.355, 0.5, 0.8 and 1 mm. Each vector component is the mass percentage of the particles within this size range in relation to the total mass of particles. According to this scheme (Fig. 1), $\underline{f}$ is the feed material size

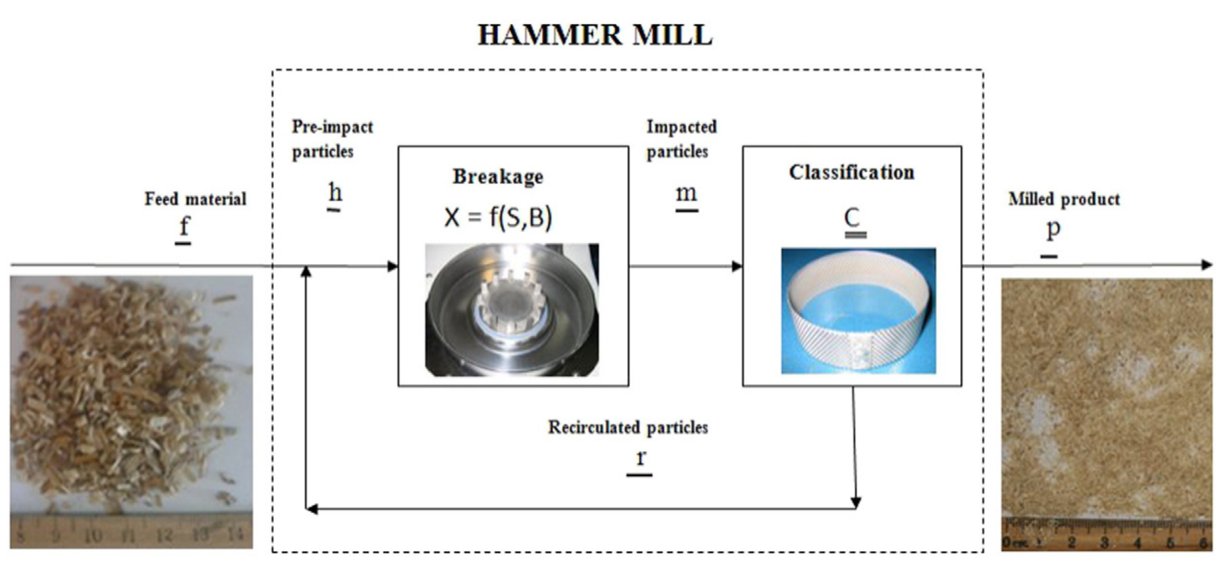

Fig. 1. Scheme of a mill combined with a classifier.