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Effects of hammer configurations on pearl millet grinding system with a hammer mill: theory and experiment

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ABSTRACT

In grinding processes using hammer mills, the configuration, number and speed of hammers are some of the main factors that can affect system performance. This paper aims to investigate the effects of hammer configurations in terms of specific energy consumption (SEC), grinding mass efficiency, and productivity. These effects were studied theoretically on the basis of classical grinding laws and experimentally with four different hammer configurations. From theoretical studies, a decreasing power model of SEC versus hammer configurations was developed, which was then validated with a determination coefficient of 0.99 in experiments using a 2 HP-DC hammer mill. The good agreement between theoretical and experimental results confirms that the specific energy consumption and the productivity are directly dependent on hammer configurations, but the effects are not significant for grinding mass efficiency.

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1. INTRODUCTION

Cereals are the staple food for Senegalese population, as in most Sahelian countries [1]-[4]. For grinding cereal grains in Senegal, the hammer mills with pulley-belt systems are widely used due to their low acquisition and maintenance costs [5]-[8]. These mills increase productivity and offer greater product diversity, but they have complex configurations with average efficiencies. To solve these problems, locally-designed hammer mills without belt pulleys have been developed and are increasingly used for cereal milling due to the availability of spare materials, ease of adjustment and low cost. However, many of these hammer mills have been improperly designed, thereby reducing their performances. To improve their performances, it is necessary to design them correctly, taking into account the factors that influence their operation. These factors include not only the quality of cereal grains, but also the effects of motor speed, the screen opening sizes and the number of hammers and also their sizes. To obtain the desired product with good grinding mass efficiency and minimum specific energy consumption (SEC), it is essential to adjust these factors individually or in combination.

The researchers [9]-[11], authors reveal that the increase of screen openings sizes, speed or number of hammers give a significant reduction in grinding energy. However, in fine grinding the shaft speed and hammer configurations are the major key components determining the specific energy required and grinding efficiency. Anderson, in [12] stated that when screen opening sizes and speed are kept constant, the increased of hammer sizes produced particles of smaller mean geometric sizes. For finished particle size, 30% is attributed to hammers-particles being grinding impacts force, that depends of size and number of hammers. Hence, optimal hammers designs will provide maximum reduction of specific energy needed for grinding.

This work focuses on investigating the effect of hammer size on grinding processes. The study was carried out using a theoretical analysis of classical grinding laws such as Bond's, Rittinger's, and Kick's, and an experimental analysis using a 2-HP hammer mill. The experiment is based on a comparison of four different hammer configurations in terms of SEC, productivity, and grinding mass efficiency.

2. MATERIALS AND METHODS

2.1. Hammer mill description and operating principle

The grinding unit consists of a hammer mill driven by a DC motor. Figure 1 shows the diagram of the hammer mill. It consists of a feed hopper and a circular grinding chamber covering the hammers and the screen. The feed hopper is used with a valve to control the flow of grains. The hammer mill used has six hammers fixed on the motor shaft, with a high speed of 4,000 rpm. The screen ensures the continuity of the cereal grains grinding until the particle sizes are smaller than screen opening sizes. Grinding is an operation designed to fragment the grains by the repeated impacts of the mechanical forces developed by hammers. Once grinded, the fine particles pass through the openings of the screen and those particles whose size is greater than the screen opening return to the grinding chamber of the mills and are again grinded by the hammers.

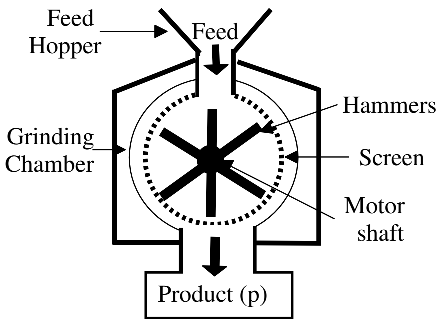

Figure 1. Diagramm of the hammer mill operating principle

2.2. Balance mass equations

The grinding process using a hammer mill can be described by a repetitive cycle of events. To establish the equations of mass balance, the structure of the grinding process model presented in Figure 2 has been proposed. The figure describes the process of grinding on the basis of the operating mechanisms of hammer mills, and takes into account internal phenomena such as mass loss during the process. The model explains that during each grinding cycle, the mass of fine particles passes through the sieve openings as the final product, while the mass of coarse particles is retained and returned directly to the mill.

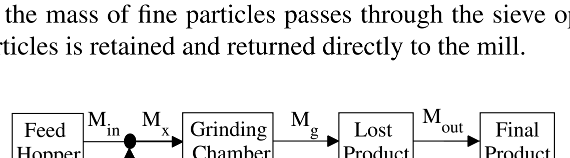

Figure 2. Symbolic representation of the grinding process

Based on this symbolic representation, the mass balance in (1).

$$\begin{cases} M_{out} = M_g - M_{los} \\ M_x = M_{in} + M_{ret} \end{cases} \quad (1)$$

Where M_{in} and M_{ret} are input and retained masses above the screen. M_{out} is the mass of product. M_g is the grinded mass and M_{los} is the mass losses.

In the grinding chamber, the particle size vary widely around the geometric mean such that there will be some large-sized and many small-sized particles due to particles-hammers interactions. Assuming that the mill behaves as a perfectly processing machine, a fraction mass is retained and another fraction passes through the screen openings. In grinding, the instantaneous total unground mass is estimated taking into account classification and breakage functions. The breakage distribution function (B_i) governs the redistribution of particles. The unground particles are redistributed by means of breakage for an eventual new grinding phase. The classification function (α_i) has the form of a cumulative distribution and computes the probability of breakage for each particle size. The mass losses due to handling and designing problems can be defined as a fraction (β_i) of grinding products. Based on these assumptions, the mass balance equations can be expressed as in (2).

$$\begin{cases} M_{los} = \beta_i M_g \\ M_{ret} = B_i \alpha_i M_x \\ M_g = (1-\alpha_i) M_x \end{cases} \quad (2)$$

By substituting (1) in (2), the output and input masses expressions can be rewritten as (3).

$$\begin{cases} M_{out} = (1-\alpha_i)(1-\beta_i) M_x \\ M_{in} = (1-B_i\alpha_i) M_x \end{cases} \quad (3)$$

2.3. Grinding mass efficiency

The grinding mass efficiency (η_m) can be defined as the ratio between the masses of the product and the cereal before grinding. Based on balance mass equations, it can be defined as (4).

$$\eta_m = \frac{M_{out}}{M_{in}} = \frac{(1-\alpha_i)(1-\beta_i)]}{[(1-B_i\alpha_i)]} \quad (4)$$

$\alpha_i(x)$ is the classification function. It is expressed according to grain sizes, particularly the size reduction ratio [13]-[15]. It is defined as the relation between the average size of product (x) and of the feed particles (x_0). The reduction ratio is given by (5).

$$\sigma(x) = \frac{x}{x_0} \quad (5)$$

The breakage distribution function is expressed using the mass fraction of the fine product (ϕ).

$$B_i(x) = \phi\sigma^m + (1-\phi)\sigma^k \quad (6)$$

k and m are cereal coefficients accounting for coarse product size distributions, and the shape of fine.

The size reduction ratio can be controlled by the screen opening sizes or by hammers impacts. Increasing hammer size increases the impact between them and the particles. In fact, the mill breakage is reduced. For the coefficient of mass losses, it is often linked to handling and design problems. It is often negligible if the mill is correctly designed. The classification function can be studied on the basis of Gates-Gaudin-Schuhmann (GGS) and Rosin-Rammler-Bennet (RR) models, considered more accurate for fine and coarse particle size distributions (PZD), respectively [16], [17]. The PZD can be represented by the cumulative passing and retaining functions. For fine particles, all grinded grains shall pass through the screen openings. Thus, the percent cumulative passing is high. In fact, for fine particles the probability of breakage is approximately 0. For large particles sizes, the percent cumulative passing is very low. Hence, the probability of breakage is approximately 1. Based on assumptions, the breakage classification function is described as (7).

$$\begin{cases} \alpha_i(x) = 0 & \text{for fine particle size} \\ \alpha_i(x) = 1-(1-\sigma(x))^n & \text{for intermediate size} \\ \alpha_i(x) = 1 & \text{for large particle size} \end{cases} \quad (7)$$

For this works, the millet grains is reduced to produce fine flour. Obviously, $\alpha_i(x)$ has the value of 0. According to the theory, it is concluded that the grinding mass efficiency can be considered as function of mass losses. The effects of hammers configurations are not significant for the grinding mass efficiency. However, it have a significant effects on the time of grinding that it is a factor that can influence the overall energy efficiency of the system.

2.4. Grinding energy studies

The determination of specific energy requirements remains one of major problems in grinding process. The energy consumed during the process depends on various parameters. For predicting the specific energy requirements, which is the ratio of net required energy per unit mass of cereals, several theoretical laws have been developed. The grinding energy theories based on the principles of the energy-size reduction relation have been proposed by the researchers [18]-[20]. In 1885, Kick established a law based on the assumption that the energy required for a given size reduction is proportional to sizes reduction ratio. Bond, in 1952, had proposed a law based of many experimental results that link the energy to the square of particle diameters. Bond postulated that the required energy for reduction is inversely proportional to the square root of the size produced. In 1967, Rittinger's law was established. It states that the required energy is proportional to the new surface area generated. The Bond's, Rittenger's, and Kick's grinding laws are expressed as in (8)-(10) [21].

$$E = K_b[\frac{1}{\sqrt{x}} - \frac{1}{\sqrt{x_0}}] \tag{8}$$

$$E = K_r[\frac{1}{x} - \frac{1}{x_0}] \tag{9}$$

$$E = K_k[lnx - lnx_0] \tag{10}$$

Where K_r, K_b and K_k are the Rittinger's, Bond's, and Kick's, constants. For the pearl Millet (Pennisetum glaucum) used in this work, x_0 is about 1.9 mm.

For fine grinding, the Rittinger's grinding theory gives better results [20]-[24]. According to Rittinger, the constant depends on the grinding method which includes the hammers, the screen, and the speed. Many scientific studies [25], [26] have shown their influence on energy consumption. Hence, the energy studies can be analysed from the impact between particles and hammers. In grinding, the particles are grinded by hammer-impacts. The total force exerted by the hammers is directly proportional to the size (z), the speed (ω) and the number (N_h) of hammers. Based on these assumptions, the specific energy is rewritten using the general form as in (11).

$$E = K_r(N_h, \omega, z)[\frac{1}{x} - \frac{1}{x_0}] \tag{11}$$

For this work, the diameter of pearl millet and the average final product size are considered constants. Assuming that the final and initial particle sizes are constant, and the hammer mill operate at constant speed with a fixed number of hammers, the specific energy can be expressed as in (12).

$$E = K \times f(z) \tag{12}$$

Since the mass of hammers before impact is much greather than the mass of a particle, the kinetic energy associated with a particle is very low compared to that associated with hammers. With this assumption, particle-particle impacts can be neglected. In a first approximation, it is assumed that when the hammer size is small, the hammer-particle impact is small and the grinding time is longer and therefore the energy consumption increases. On the other hand, an increase in the size of the hammers leads to higher hammer-particle impacts. As a result, time becomes shorter and energy consumption decreases. In a second approximation, it should be noted that for the same operating speed and the same screen opening size, the energy required to grind the same amount is lower for larger hammers. Therefore, specific energy laws can be defined as a decreasing analytic function. In this work, we assume that the decreasing degree (υ) depends directly on the design parameters and the grinding method. In a three approximation, lower values for hammer sizes correspond to a higher energy required. Therefore, a coefficient δ related to the initial value of energy for small hammers sizes are considered for modelling. Based on assumptions, a model of SEC is proposed in the form of (13) taking into account the energy limit value for hammers with small references.

$$E(z) = \mu z^{-\upsilon} + \delta \tag{13}$$

The three constant factors μ, υ, and δ were obtained from fitted approach using the experimental results of specific energy and hammer sizes. The energy-size of hammer principles is formulated on the basis on many assumptions, but nevertheless, we believe that this theoretical analysis is qualitatively correct and could explain some of the differences observed in the mass and energy grinding efficiencies of mills, particularly for hammer mill locally designed.

2.5. Experiments

Experiments were carried out to analyse the effects of hammer sizes on the specific energy consumption (SEC), productivity and grinding mass efficiency. It was conduct using a 2 HP DC hammer mill with four hammer sizes. For each grinding test, 10 kg of pearl millet and a screen with open size of 1 mm were used. During each test, the instantaneous power requirement, the time, and the ground millet were measured. The hourly productivity was derived from the mass of pearl millet and the grinding time, and SEC was derived from the average power and hourly productivity. Hence, the hourly productivity and SEC were expressed as (14) and (15).

$$\text{Hourly productivity} = \frac{\text{Mass of pearl millet}}{\text{Grinding time}} \tag{14}$$

$$\text{SEC} = \frac{\text{Power comsumed}}{\text{Hourly productivity}} \tag{15}$$

The coefficient of mass losses (β_i) is calculated using the (16).

$$\beta_i = \frac{\text{Mass of pearl millet - Mass of flour}}{\text{Mass of pearl millet}} \tag{16}$$

3. RESULTS AND DISCUSSION

In this section, four hammer types are evaluated. For each type of hammer, SEC, productivity, and system efficiency are determined. Table 1 give the obtained results.

Table 1. Experimental results for hammer configurations

Hammers (mm x mm)	Power (W)	Product mass (kg)	Time (mn)	Q (kg/h)	SEC (Wh/kg)
HM_1 (35x20)	1558.39	9.4	38.46	15.6	99.9
HM_2 (46x20)	1388.79	9.4	19.23	31.2	44.51
HM_3 (61x20)	1424.79	9.55	16.13	37.2	38.30
HM_4 (76x20)	1530	9.4	15.15	39.6	38.64

3.1. Productivity and specific energy consumption

The grinding time, SEC, and productivity for different hammer types are shown Figures 3-5. The results show that the grinding time is longer with the smaller hammers. These results demonstrate that when the same mills are used at the same speed and with the same screen, the mill with larger hammers has a faster hammer-tip speed, which increases hammers-particle impacts. As a result, the time needed to grind the millet grains is reduced compared to the mill with smaller hammers, which needs more time to achieve the grinding process.

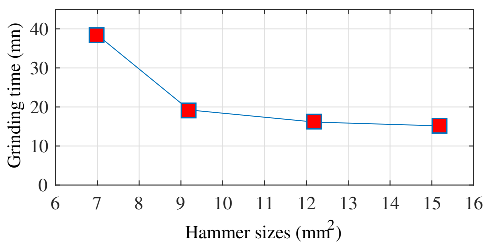

Figure 3. Grinting time versus hammer types

The results show that productivity increases with increasing hammer sizes, and, inversely, the SEC decreases with increasing hammer sizes, as shown in Figures 4 and 5 and Table 1. The hourly productivity increased from 15.6 to 39.6 kg/h and the SEC decreased from 99.9 to 39.8 Wh/kg for a variation in hammer size from 7 to 15.2 mm^2. These results are explained partly by the fact that the power required to drive the hammer mill is practically constant and the grinding time decreases with with increasing hammer sizes. In fact, small hammers need more time to grind the desired millet quantity. Thus, on the one hand, the reduction of grinding time by the use of larger hammers, allows to reduce the SEC significantly, and on the other hand to improve productivity.

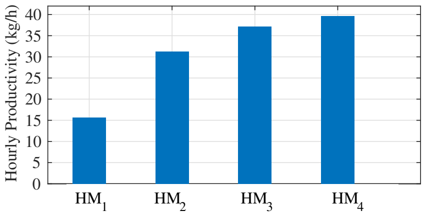

Figure 4. Productivity versus hammer types

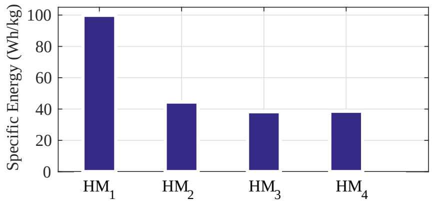

Figure 5. Specific energy versus hammer types

3.2. Grinding mass efficiency

In this subsection, the effect of hammer configurations was evaluated by studying the grinding mass efficiency and hammer sizes relationship. The mass of obtained product is given in Table 1. From it, the coefficient of mass losses versus hammer configurations can be calculated. From results, it can be seen that the influence is not significant and the coefficient of mass losses is around 6%. In fine grinding, all the ground pearl millet mass probably passes through the screen openings sizes. The difference, depending on hammers used, is in the grinding time. Thus, the mass losses are due to handling problems. This result presented in Figure 6 clarifies that the mass losses are independent of hammer configurations used with a mean grinding mass efficiency of around 94.3%. However, it can have a significant effect in terms of grinding energy efficiency and of product quality particularly in nutritional composition.

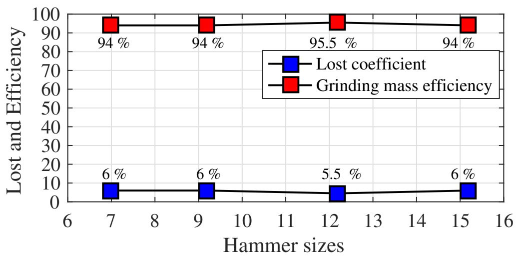

Figure 6. Lost and grinding mass efficiency

3.3. Fitting model to SEC data

The parameters of the energy model were determined by fitting the theoretical analysis to experimental results. Thus, specific energy versus hammer sizesizes relationships was fitted with a coefficient of determination R^2 of 0.99. A second-order decreasing power function fitted the data well, as shown in Figure 7.

Table 2 presents the estimated model parameters. The result indicates the good fit of this model. However, the predicted model is many assumptions and the parameters are function of the physical and dimensional properties, and grinding method such as surface area, sphericity, dimensional properties, the size of particles, moisture content, the screen openings. Hence, the proposed model can be ameliorated taking also into account effects of other parameters neglected in this work.

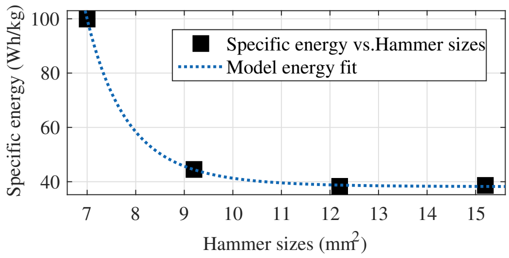

Figure 7. Fitting model to SEC

Table 2. Fitted model parameters

Parameters	μ	υ	δ
Values (with 95% confidence bounds)	$7.18^{-8}(-7.36710^9, 8.80310^9)$	8.361 (14.18, 2.546)	38.16 (32.08, 44.24)

4. CONCLUSION

In grinding processes, hammer design is one of the most important factors likely to affect the hammer mill performances. This present work provides a study of the effects of hammer configurations in terms of grinding mass efficiency, productivity and energy consumption. Results obtained from theoretical and experimental studies with four hammer configurations illustrate the possibility of improving productivity and specific energy requirements by using appropriate hammers on the one hand. Studies have also shown that hammer configuration has no significant impact on grinding mass efficiency. On the other hand, on the basis of grinding laws and experimental data, a decreasing power model of SEC versus hammer configurations was developed and then validated with a coefficient of determination of 0.99. This result demonstrates the good agreement between the theorical and experimental results.

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