SOME STATISTICAL PARAMETERS FOR *MISCANTHUS GIGANTEUS* AND *SALIX VIMINALIS* GRINDING USING HAMMER MILLS

Gheorghe Voicu[1], **Georgiana Moiceanu**[1], **Mihai Chitoiu**[1], **Petru Cardei**[2]
[1]University Politehnica of Bucharest, Romania; [2]National Institute of Research-Development for Machines and Installations Designed to Agriculture and Food Industry, Romania
ghvoicu_2005@yahoo.com, moiceanugeorgiana@gmail.com, petru_cardei@yahoo.com

Abstract. In the present paper we present values of some parameters of the grinding process experimentally determined for a hammer mill used for grinding miscanthus stems and willow harvested with specific harvesting machines. The grinding energy according to three tuning parameters was determined: hammer rotor frequency, feeding flow and mill sieve orifice diameter, for two types of hammers (one or twoedge corners). Value sets of energy-feeding flow, energy – rotor rotation frequency, energy – sieve orifice diameter, were analyzed, statistically determining the correlation between them, as well as other statistical parameters, using Excel MS Office (ex.covariance or kurtosis). If grinded biomass is willow, for the link between the energy and sieve orifice diameter the correlation shows a weak relation for one and two edge corner hammers, the two parameters being inversely proportional. Keeping in mind the fact that in the seven out of eight cases the correlation energy sieve orifice diameter presents an inversely proportional dependency, we can accept the hypothesis of reverse proportionality of the two parameters. In the paper, other comments are added regarding values obtained for all statistical parameters analyzed for the two types of grinded biomass.

Keywords: biomass, grinding, energy consumption, frequency, feeding flow, statistical parameters.

Introduction

Between the constructive and functional parameters with a high influence on the hammer mill work rate, we can count: hammer rotor dimensions, dimension and shape of the hammer, dimension and form of the sieve orifices, rotor speed, feeding flow, etc.

The authors [1] have studied the consumed specific energy variation in hammer mills according to the sieve orifice diameter and grinded vegetal material (alfalfa) mechanical properties. The first conclusion of the article is that specific energy consumption rises with lowering the sieve orifice diameter. Using only linear regression, the authors [1] obtain a regression coefficient with the values of 0.68-0.7. Using polynomial non-linear regressions, regression coefficients of over 0.7 were obtained, reaching over 0.9.

The authors [2] confirm direct dependency of energy consumption on hammer mills with the rotation speed, which seems normal, the same thing being confirmed by the authors of the paper [3], which additionally shows reverse dependency of the same energy with the sieve orifice diameter.

Reverse dependency of energy with the sieve orifice size is presented in [4], in which it is stated that the linear model of dependency of consumed energy on model parameters gave the best results. In paper [5], the rise in consumed energy with lowering of the sieve orifice dimensions is outlined, but also the rise of energy consumption with material humidity, of course, for the interval of humidity levels taken into consideration.

The authors [6] confirm the same types of dependency, and the authors [7] confirm direct dependency of energy consumption on the work flow (which also means productivity in this case), but also on the mechanical properties of the grinded material.

In paper [8] the same reverse dependency between the consumed specific energy and the sieve orifice dimensions is shown. There are some gaps from the monotony of this dependency, as it can be observed from the graphical representation from [8]. Also, in [8] results and suggestions on classical distributions, which can model grinded material distribution by dimensions, are given. Published research in the article [9], confirms the rise in consumed specific energy with a reduction in the sieve orifice dimension, also it outlines the rise of the production capacity with a rise in the sieve orifice dimensions. Also, [9] shows the effect on grinded material by humidity effect. [9] confirms a rise in the working capacity with a rise in the sieve orifice diameter. Selection of optimal working regimes is achieved on experimental data, and not interpolated data. The hammer mill working process is presented also in papers [10-13].

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Paper [10] also confirms a rise of energy consumption with a lowering of the sieve orifice diameter, rising the work capacity with a rise of the sieve orifice diameter and a rise of energy consumption with a rise of material humidity. In paper [11], continuing the research of the authors on the subject, rise of the consumed specific energy in the process of grinding with a rise of the rotor rotation speed (rise of frequency) is confirmed, lower consumption of the same energy with a lowering of the sieve orifice diameter, conclusions available for total energy. Also, paper [11] confirms a drop in the consumed total specific energy with a rise in the feeding flow. Effective specific energy though seems to have a maximum in accordance with the feeding flow. Also, in [11] the authors create an optimization of the consumed specific total energy.

The purpose of the paper is to demonstrate (or at least to outline) that statistical parameters can be used inclusively for establishing energy correlation or dependency at grinding with constructive, respectively functional parameters of hammer mills used for size reduction of energetic biomass (*Miscanthus giganteus* or *Salix viminalis*).

Materials and methods

Experiments regarding energy consumption of a MC-22 hammer mill (Romania) on biomass grinding of Miscanthus and willow were realized. The mill is equipped with an electric motor of 22 kW, speed of 3000 rpm (revolutions per minute), having a 0.33-0.50 kg·s^{-1}productivity on grinding corn stalks, respectively 0.22-0.42 kg·s^{-1} on grinding packaged hay, using a sieve with ∅4 mm orifice size. Hammer rotor diameter (for disc distributed orifices) is of 220 mm, and its length is of 500 mm. The rotor is equipped with 24 hammers of 135 mm length in parallel distribution (see Fig. 1).

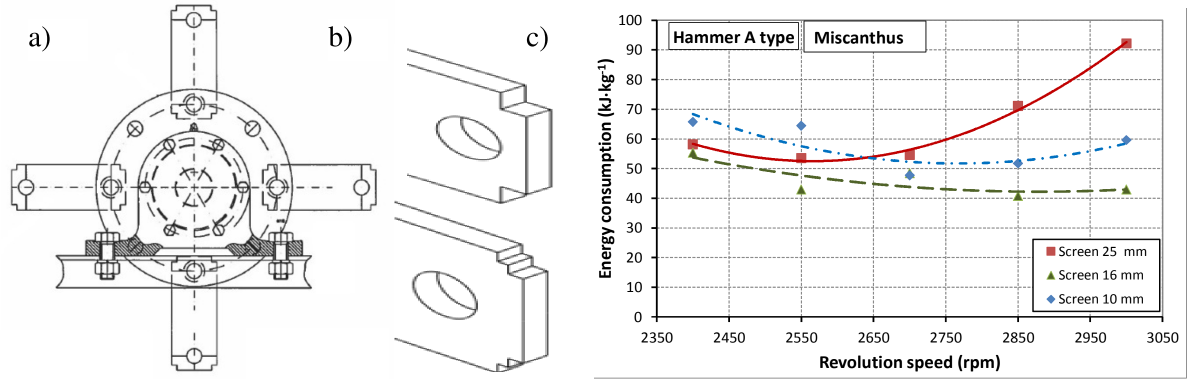

Fig. 1. **Hammer mill rotor MC-22 (a); hammers with one and two edge corners (b); specific energy vs. rotor speed and sieve orifice size (c)**

Biomass from energetic plants was made out of *Miscanthus giganteus* stems, harvested with a special harvester, fragments obtained having an average size of 125 mm, as well as from grinded willow *Salixviminalis*, harvested using a specially designed machine, having fragments of size between 25-47 mm.

Miscanthus biomass humidity was between 8.11-11.31 % (medium moisture content – 10.3 %). Energetic willow biomass had a 38-45 % humidity level at harvesting time, but its milling was done after 3.5 months, when average humidity was between 8.89-11.99 %. Miscanthus biomass quantity was 5 kg every time, but the time for grinding was different from one probe to the next. This also applied for grinded willow biomass. Based on these parameters, it was possible to calculate the material feed rate.

During probing, grinding energy was determined in relation to three other parameters: five hammer rotor frequencies, more material feeding flow values, three or four diameters for mill sieve orifice, for two types of hammers (with one or two edge corners). The results obtained in the experiments are presented in Table 1, respectively Table 2.

For describing some system internal relations, as well as for describing relations between output and input sizes and control, there are no applicable physical relations. This situation is due to the highly hazardous character of the hammer mill working process. In these conditions, relations that mathematically describe connections between the system (process) parameters are researched through statistical modelling. More exactly, this refers to, in the present case, obtaining better statistical regressions for the main process quality parameters. After this, relations are used for searching and identifying the optimal working points in the process parametric space.We tried to identify possible connections between the consumed energy in the grinding process and the mill rotor rotation frequency, size of sieve orifices and material feeding flow for different types of hammers.

Table 1

Grinding energy variation in relation with hammer mill parameters

Sieve holes diameter, mm	**Rotor frequency, Hz**	**Feeding rate, $kg \cdot s^{-1}$**	**Energy, $kJ \cdot kg^{-1}$**	**Sieve holes diameter, mm**	**Rotor frequency, Hz**	**Feeding rate, $kg \cdot s^{-1}$**	**Energy, $kJ \cdot kg^{-1}$**
Biomass of *Miscanthus giganteus*							
Hammer with one-edge corners				Hammer with two-edge corners			
25	50.0	0.144	92.213	25	50.0	0.250	114.282
25	47.5	0.185	71.113	25	47.5	0.250	102.136
25	45.0	0.214	54.561	25	45.0	0.208	76.845
25	42.5	0.150	53.558	25	42.5	0.147	80.857
25	40.0	0.129	58.156	25	40.0	0.200	48.449
16	50.0	0.225	42.934	16	50.0	0.172	94.961
16	47.5	0.227	40.811	16	47.5	0.192	72.357
16	45.0	0.135	48.437	16	45.0	0.167	88.193
16	42.5	0.121	42.956	16	42.5	0.143	67.108
16	40.0	0.129	55.320	16	40.0	0.167	96.524
10	50.0	0.217	59.631	10	50.0	0.185	169.178
10	47.5	0.192	51.797	10	47.5	0.143	126.360
10	45.0	0.167	47.738	10	45.0	0.192	78.992
10	42.5	0.167	64.424	10	42.5	0.167	105.104
10	40.0	0.116	65.717	10	40.0	0.116	176.305
7	50.0	0.139	102.091	7	50.0	0.119	169.178
7	47.5	0.156	125.134	7	47.5	0.143	126.360
7	45.0	0.128	108.604	7	45.0	0.139	78.993
7	42.5	0.135	76.676	7	42.5	0.116	105.104
7	40.0	0.1	68.106	7	40.0	0.100	176.305
Biomass of *Salix viminalis*							
16	50.0	0.385	30.495	16	50.0	0.357	44.032
16	47.5	0.417	28.359	16	47.5	0.417	33.110
16	45.0	0.385	26.839	16	45.0	0.357	29.606
16	42.5	0.313	40.8549	16	42.5	0.333	25.590
16	40.0	0.278	32.7179	16	40.0	0.263	28.700
10	50.0	0.333	42.809	10	50.0	0.556	34.120
10	47.5	0.385	40.2549	10	47.5	0.500	33.422
10	45.0	0.417	35.6959	10	45.0	0.455	29.168
10	42.5	0.313	45.5339	10	42.5	0.357	35.949
10	40.0	0.2	49.5719	10	40.0	0.357	28.371
7	50.0	0.417	40.959	7	50.0	0.500	33.434
7	47.5	0.238	57.615	7	47.5	0.500	35.083
7	45.0	0.417	30.738	7	45.0	0.500	29.649
7	42.5	0.295	42.295	7	42.5	0.333	47.729
7	40	0.357	27.171	7	40	0.25	45.044

Given the fact that there were no similar repetitions of the experiments, pairs of values: energy – feeding flow, energy – rotation frequency, energy – sieve orifice diameter, were statistically analyzed, determining correlation (corr) between them, determination coefficient R^2, linear regression line b, covariance(cov) and kurtosis coefficient (kurt), using Excel MS Office calculus software. Calculus relations are presented as the following:

$$\mathrm{corr}(x,y)=\frac{\sum_i (x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_i (x_i-\bar{x})^2 (y_i-\bar{y})^2}}, \tag{1}$$

$$R^2=\frac{\sum_i (y_i-\bar{y})^2-\sum_i (y_i-\hat{y})^2}{\sum_i (y_i-\bar{y})^2}, \tag{2}$$

$$b=\frac{\sum_i (x_i-\bar{x})(y_i-\bar{y})}{\sum_i (x_i-\bar{x})^2}, \tag{3}$$

$$\mathrm{cov}_p(x,y)=\frac{1}{n}\sum_i (x_i-\bar{x})(y_i-\bar{y}), \tag{4}$$

$$\mathrm{cov}_s(x,y)=\frac{1}{n-1}\sum_i (x_i-\bar{x})(y_i-\bar{y}), \tag{5}$$

$$\mathrm{kurt}(x)+\left\{\frac{n(n+1)}{(n-1)(n-2)(n-3)}\sum\left(\frac{x_i-\bar{x}}{s}\right)^4\right\}-\frac{3(n-1)^2}{(n-2)(n-3)}, \tag{6}$$

where $i = 1\ldots n$ – number of experiments;
x_i, y_i – sets of values obtained in experiments;
$\bar{x}$, $\bar{y}$ – value average x_i, respectively y_i;
s – standard deviation;
b – linear regression slope.

Results and discussion

The statistical analysis results are presented in Table 3. The analyzed data presented in the table, both for Miscanthus and willow, show a correlation of energy with the sieve orifice diameter, without a negative exception, which proves that there is a relation between these parameters, it is almost a reverse proportionality.

This conclusion is in concordance, with no exception, with all specialty literature linked to hammer mills and other mills [1-11]. The same phenomenon takes place in the case of energy and flow of material introduced for grinding correlation, being also with no negative exception, meaning that, if there is a link between these parameters, it is close to reverse proportionality. The conclusion is less firm than the last one and is in accordance with some papers [11], but is in contradiction with others [7]. In this sense, the definition of each author for the consumed specific energy must be verified.

In the case of energy and rotor frequency correlation (implying also the rotor speed), it is a positive correlation for mills equipped with one or twoedge corner hammer rotor. Statistically, we can test a proportional dependency in over 87.5 % of cases.

Importance of frequency (speed) is outlined in many specialty papers, especially for grinded material granulation realization [2].

According to statistics, in the case of one-edge hammer, relation between the energy and sieve orifice diameter is weak, and in the case of two-edge hammer it is moderate for Miscanthus biomass and weak to moderate for willow biomass in both hammer type cases.

For Miscanthus biomass, in the case of relation between the consumed energy and rotor frequency, the experimental results show, as well, a weak correlation (obtained values were very small) and for the connection between the consumed energy and feeding flow, correlation shows a weak relation in the case of one corner edge hammer, respectively a moderate one for two edge-corner hammers. For willow biomass correlation it shows a moderate relation of energy with the feeding flow for both types of hammers.

Table 3

Statistical characteristics regarding the correlation between energy and tuning and command parameters, for grinding energetical plants

Parameter pair	**Correlation (rel.1)**	**Determination coefficient, R^2 (rel.2)**	**Regression linear slope (rel.3)**	**Covariance *P* (rel.4)**	**Kurtosis (rel.6)**
Biomass of *miscanthus x giganteus*					
Hammer with one-edge corners					
Energy – Sieve holes diameter	-0.349	0.122	-1.164	-54.999	-0.603
Energy – Rotor frequency	0.232	0.054	1.504	18.798	4.122
Energy – Feeding rate	-0.329	0.109	-199.03	-0.286	0.177
Hammer with two-edge corners					
Energy – Sieve holes diameter	-0.627	0.393	-2.969	-140.279	-0.571
Energy – Rotor frequency	0.153	0.024	1.691	21.134	0.591
Energy – Feeding rate	-0.635	0.404	-398.64	-0.659	-0.900
Biomass of *salixviminalis*					
Hammer with one-edge corners					
Energy – Sieve holes diameter	-0.439	0.193	-1.013	-14.180	-1.098
Energy – Rotor frequency	0.039	0.002	0.095	1.192	-0.137
Energy – Feeding rate	-0.690	0.476	-88.970	-0.39831	-1.605
Hammer with two-edge corners					
Energy – Sieve holes diameter	-0.550	0.303	-0.570	-7.973	-1.192
Energy – Rotor frequency	0.505	0.255	0.151	1.882	-1.274
Energy – Feeding rate	-0.481	0.231	-16.645	-0.139	-1.7345

For dependency between the energy and rotor speed, with hammers, in the case of grinded willow, correlation is always positive (so a direct dependency is suggested), but insignificant for the case of hammer mills with one edge-corner hammers, and a moderate for a mill equipped with two edge-corner hammers. Taking into consideration the obtained results, we can give the hypothesis of a proportional variation of energy with rotor frequency (not necessarily linear).

Without exception, for all experiments (Miscanthus and willow) the variation energy – feeding flow is reversed. As such, the hypothesis of inverse variation of energy with the flow is certitude (at least in the case of our experiments). In the case of determining coefficient R^2, our experiments showed its values as small, which shows that the feeding flow influence on the consumed energy is slightly significant.

The linear regression curve between energy and the three variables shows, in certain limits, that the data are in direct dependency (positive curve) or in reverse dependency (negative curve).

Kurtosis represents the flattening degree of distribution, characterizing the relative peak or its flattening in comparison to normal distribution. Positive kurtosis indicates a relatively high distribution. Negative kurtosis indicates relatively smooth distribution. We can observe (based on the data presented in the table) that value distribution is relatively flat for most experimental data and only in the case of Miscanthus biomass and only energy distribution in relation with the rotor frequency can be relatively high.

Covariance is an absolute indicator of the link between variables and shows how much two variables modify together, determining an average of error products. So, positive values of covariation show a direct link of energy with the hammer rotor frequency, but its negative values show a reverse link of energy with the size of the sieve orifices, respectively with the feeding flow.

Thus, from the paragraphs presented above it can be stated that the data obtained in our paper after experimental research are according to other results obtained by various researchers around the world.

Conclusions

1. Hammer mill work process parameter variability, especially in the case of physical-mechanical properties of materials subjected to grinding, leads to extremely varied experimental results, even if the process is controlled from the outside.
2. The present paper presents experimental data obtained from Miscanthus and willow grinding (harvested in fragmented state) using a hammer mill, equipped with two types of hammers, to which the rotor speed and sieve orifice diameter, and also the feeding flow were modified, and for which the consumed specific energy for grinding was measured.
3. Experimental data were statistically processed for establishing the link between the process parameters.
4. All determined statistical parameters present the same types of links between the energy and frequency of rotor frequency, sieve orifice diameter and the feeding flow for both types of hammers.
5. It was established that between the consumed energy and mill rotor rotation frequency there is a direct proportional link, while the relation between the energy and sieve orifice diameter is of reverse proportional type for most experiments. Also, from a statistical point of view, the link between the energy and feeding flow is preponderantly negative, mainly of reverse proportionality type.
6. The results obtained and presented in the paper prove that the analysis method for the relation between some physical process parameters (in our case the grinding process with hammer mills) on the basis of some statistical parameters can be used successfully for identifying the link type and its size through obtained statistical values.

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