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ENERGY CONSUMPTION ANALYSIS ON ENERGETIC PLANT BIOMASS GRINDING USING HAMMER MILLS

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Harvest pre-grinded biomass comminution process using hammer mills has a wide range of influencing factors. Both grinded material physical-mechanical properties (density, moisture, volume mass) as well as grinding equipment constructive and functional parameters can be outlined.

For grinding Miscanthus, willow respectively, some process parameters were modified, and necessary grinding power and grinding degree have been determined. For obtained experimental data, the Π Theorem in Dimensional Analysis was applied in order to identify power dependency and for grinded material dimension with other process parameters (rotor speed, feeding flow, sieve orifice dimensions).

Keywords: biomass comminution, hammer mill, miscanthus, willow, grinding process, dimensional analysis

1. Introduction

Current situation regarding global warming phenomenon is a global concern and oil use is regarded as the main factor for the greenhouse effect, a fact which has led scientific communities to research alternative sources of energy, with a high accent on renewable energy sources.

Biomass is commonly regarded as a future substitute, or at least a combined solution, for many oil using applications [1-4].

Biomass is the biggest source of renewable energy in the EU and is expected to make a significant contribution to the 20% EU renewable energy target by 2020. Given the fact that oil is a fast depleting natural resource, efforts to better understand and apply fuels based on biomass, efforts across the globe for cutting edge researches on the subject are being implemented.

Biomass comminution researches around the world are mainly focused on herbaceous biomass and experimental tests are realized using different mill types, like cutting, knife or hammer mills [5].

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Mechanical preprocessing is the first step in taking biomass, typically in baled format, or woody feedstocks in log or slash format, from the harvesting location and chopping, shredding, grinding, chipping or other means of size reducing the material in preparation to supply the feedstock for a pelletizing factory. However, current understanding accepts that the characteristics of raw biomass are unable to meet the requirements of both logistic and fuel conversion systems and must be upgraded prior to delivery at the bio refinery plant gate [6]. Biomass particle shape data is crucial in mill classifier and burner design and optimization, but there is only limited experimental data available in literature [7].

Hammer mills are the most popular equipment used for bioenergy application researches, and biomass is often densified to improve transportation, conveying, and comminution in the power stations, densification being a key factor for improvement, given the vast amount of energy this process is consuming [8].

Optimal grinder configuration for maximal process throughput and efficiency is strongly dependent on feedstock type and properties, such as moisture content. Tests conducted using a HG200 hammer grinder indicate that tip speed, screen size and optimizing hammer geometry can increase grinder throughput as much as 400% [9].

Kwande et al., following specific tests, showed that by comparing mill characteristics with the breakage characteristics of the feed material, and the performance of different mills, different operating states can be evaluated. The comminution behavior of a mill is characterized by the frequency of stress events and by the stress energy acting at each stress level [10].

Optimizing hammer mills work flow is also researched in [9], using five hammer types, for grinding three types feedstock which contains miscanthus, similar to our case. A general methodology presentation in mechanical processing is offered and afterwards experimental results which show an enhancement on grinding through hammer mill configuration optimization or through grinding with an assisted pneumatic hammer and enhancing the control on particle dimensions and particle size distribution through adequate selection of grinding regime parameters are presented. Grinding equipment optimum configuration for a maximum processing capacity and maximum efficiency, according to [9], largely depends on the type of used material and its properties, including moisture content. Applied tests using a HG200 hammer mill indicated that choosing the right peripheral speed, dimension of sieve orifices and hammer geometry can lead to a rise in grinded material quantity of over 400%. No mentions of consumed energy forecast or of optimal parametrical combinations for minimizing energy consumption were made.

Other research results regarding working process, biomass grinding energy consumption, and quality indices of hammer mills process are presented in papers [11-15].

In the present paper, the work process of a MC-22 hammer mill, [16], was analyzed, using dimensional analysis. This type of data processing is a method of physical problem simplification through dimensional homogeneity application in order to reduce the number of relevant variables in the grinding process [17]. On the basis of dimensional analysis, the rotor activation power equation in relation to other process parameters was determined, and resulted values were compared with experimental results obtained in different work conditions, for two types of biomass.

2. Material and method

Experimental results that were used for dimensional analysis took place at INMA Bucharest. Miscanthus and willow biomass was used, harvested in chopped form from the institute's experimental field, with special croppers. This biomass was subjected to grinding process with the help of MC-22 hammer mill, [16], with articulated hammers, with 500 mm rotor length, hammer distribution diameter ϕ220 mm, and grinding chamber diameter of ϕ500 mm. The sieve used in experiments was interchangeable, with orifices of 25, 16, 10 and 7 mm for miscanthus biomass and 16, 10 and 7 mm for willow biomass. After harvesting miscanthus chips had an average length of approximately 125 mm, while willow particles had an average dimension of 25–47 mm (initial dimensions prior to grinding).

Also, material moisture had an average value of 9.74–11.05% for *Miscanthus giganteus* biomass and 10.67% for willow biomass.

During experimental determinations mill functional parameters were modified: sieve orifice dimension (ϕ7 mm, ϕ10 mm, ϕ16 mm, ϕ25 mm), rotor work speed (3000 rpm, 2850 rpm, 2700 rpm, 2550 rpm, 2400 rpm), as well as hammer types that were used: hammers with one-edge corner, two-edge corners, three edge corners and oblique corners (at 60°).

The quantity of material used in experiments was of 5 kg for Miscanthus, and 5,4 and 3 kg for willow, probe time being resulted from experiment (when the entire quantity of material was finished). On the basis of these values material feeding flow was calculated. Obtained centralized results for experimental determinations, both for miscanthus and willow, are presented in table 1 and table 2.

For theoretical study we applied dimensional analysis theory, with the purpose of establishing a mathematical model for the grinding process. Through this analysis we followed necessary power prediction for mill activation, both for Miscanthus biomass, as well as for energetic willow. Mathematical modelling was realized by applying the Buckingham Π Theorem [18,19].

Table 1

Data obtained during experimental tests for *Miscanthus Giganteus*

Miscanthus Giganteus									
Sieve diameter (mm)	**Revolution speed** (Hz)	**Flow** (kg/s)	**Consumed power** (kW)	**Grinded particle diameter** (mm)	**Sieve diameter** (mm)	**Revolution speed** (Hz)	**Flow** (kg/s)	**Consumed power** (kW)	**Grinded particle diameter** (mm)
Hammer with one-edge corners					Hammer with three-edge corners				
25	3000	0.144	13.31	17.65	25	3000	0.294	17.54	23.08
25	2850	0.185	13.17	14.29	25	2850	0.357	14.69	21.00
25	2700	0.214	11.69	20.17	25	2700	0.312	9.54	22.01
25	2550	0.149	8.02	20.54	25	2550	0.277	9.74	23.64
25	2400	0.128	7.47	23.29	25	2400	0.294	11.09	22.02
16	3000	0.224	9.65	18.04	16	3000	0.25	16.08	14.22
16	2850	0.227	9.28	16.65	16	2850	0.151	14.19	16.15
16	2700	0.135	6.55	16.80	16	2700	0.208	12.39	18.07
16	2550	0.121	5.21	17.24	16	2550	0.217	12.18	16.62
16	2400	0.128	7.13	17.28	16	2400	0.166	11.30	13.07
10	3000	0.217	12.96	8.56	10	3000	0.161	16.59	9.53
10	2850	0.192	9.96	8.76	10	2850	0.147	14.65	9.64
10	2700	0.166	7.96	8.81	10	2700	0.142	13.75	9.50
10	2550	0.166	10.74	10.94	10	2550	0.156	10.87	10.07
10	2400	0.116	7.64	8.92	10	2400	0.125	12.21	10.14
Hammer with two-edge corners					Hammer with oblique corners				
25	3000	0.25	15.81	17.92	25	3000	0.263	13.62	22.33
25	2850	0.25	13.03	18.81	25	2850	0.166	12.17	23.37
25	2700	0.208	11.54	16.31	25	2700	0.161	10.64	24.17
25	2550	0.147	11.54	21.03	25	2550	0.166	14.48	24.81
25	2400	0.2	11.30	21.26	25	2400	0.178	13.02	23.86
16	3000	0.172	19.70	15.48	16	3000	0.312	13.98	14.00
16	2850	0.1928	19.64	14.85	16	2850	0.238	12.47	16.72
16	2700	0.166	12.81	15.87	16	2700	0.294	11.22	20.00
16	2550	0.142	11.55	15.62	16	2550	0.208	14.37	18.26
16	2400	0.166	8.07	16.68	16	2400	0.125	8.81	17.45
10	3000	0.185	17.59	8.70	10	3000	0.192	13.84	11.04
10	2850	0.142	10.34	8.95	10	2850	0.151	13.87	11.17
10	2700	0.192	16.96	9.42	10	2700	0.138	15.86	10.71
10	2550	0.166	11.18	9.45	10	2550	0.111	11.15	10.85
10	2400	0.116	11.22	10.63	10	2400	0.108	9.61	11.10

Table 2

Data obtained during experimental tests for *Salix viminalis*

Salix viminalis									
Sieve diameter (mm)	**Revolution speed** (Hz)	**Flow** (kg/s)	**Consumed power** (kW)	**Grinded particle diameter** (mm)	**Sieve diameter** (mm)	**Revolution speed** (Hz)	**Flow** (kg/s)	**Consumed power** (kW)	**Grinded particle diameter** (mm)
Hammer with one-edge corners					Hammer with three-edge corners				
16	3000	0.385	11.73	10.40	16	3000	0.4	13.10	9.24
16	2850	0.417	11.82	9.40	16	2850	0.333	11.19	10.27
16	2700	0.385	10.32	10.76	16	2700	0.333	10.54	9.85
16	2550	0.313	12.77	10.56	16	2550	0.286	8.29	10.95
16	2400	0.278	9.09	10.80	16	2400	0.308	6.43	11.51
10	3000	0.333	14.27	8.02	10	3000	0.286	13.59	7.41
10	2850	0.385	15.48	7.56	10	2850	0.267	12.62	8.05
10	2700	0.417	14.87	6.73	10	2700	0.286	7.98	8.29
10	2550	0.313	14.23	7.89	10	2550	0.286	8.47	7.81
10	2400	0.2	9.91	9.20	10	2400	0.267	10.81	8.21
7	3000	0.417	17.07	6.50	7	3000	0.267	15.40	5.30
7	2850	0.238	13.72	5.71	7	2850	0.267	13.64	6.10
7	2700	0.417	12.81	5.92	7	2700	0.444	11.64	5.83
7	2550	0.295	12.44	5.94	7	2550	0.286	11.11	6.07
7	2400	0.357	9.70	5.19	7	2400	0.191	7.64	6.22
Hammer with two-edge corners					Hammer with oblique corners				
16	3000	0.357	15.73	9.51	16	3000	0.231	13.72	11.65
16	2850	0.417	13.80	9.75	16	2850	0.25	10.24	11.56
16	2700	0.357	10.57	9.82	16	2700	0.25	8.75	11.94
16	2550	0.333	8.53	11.62	16	2550	0.2	7.28	11.35
16	2400	0.263	7.55	11.16	16	2400	0.176	6.03	9.77
10	3000	0.556	18.96	7.36	10	3000	0.333	12.28	7.57
10	2850	0.500	16.71	7.56	10	2850	0.375	11.46	8.52
10	2700	0.455	13.26	7.65	10	2700	0.333	8.98	7.50
10	2550	0.357	12.84	7.80	10	2550	0.333	7.97	8.87
10	2400	0.357	10.13	7.59	10	2400	0.214	7.61	9.31
7	3000	0.500	16.72	5.98	7	3000	0.333	11.31	6.07
7	2850	0.500	17.54	5.40	7	2850	0.3	8.28	6.59
7	2700	0.500	14.82	5.55	7	2700	0.273	9.51	6.43
7	2550	0.333	15.91	5.84	7	2550	0.231	9.74	6.42
7	2400	0.25	11.26	6.10	7	2400	0.2	7.24	5.68

According to this theorem, the number of independent criteria from the criterial function is given by the difference *n-r*, where n is the dimensional variables and constants number, and r is the dimensional matrix class, which is equal to the number of fundamental sizes on which analysis variables can be expressed. The number of fundamental sizes is relatively small and depends on the phenomenon complexity.

Taking into consideration the experimental researches realized on the hammer mill working process, in the theoretical study we considered a number of 5 main parameters which influence the process: consumed power during working process time P [kg·m^2/s^3], particle dimension after grinding d_m [m], hammer mill rotor speed, n [s^{-1}], hammer mill sieve orifice dimension D_s [m], feeding flow Q [kg/s].

Implicit function which dimensionally *describes the grinding process*, where all terms are homogeneously dimensional in relation to the fundamental sizes from International System (L, M, T) is:

$$f(P, D_s, Q, n, d_m) = 0 \quad (1)$$

We considered the group (P, D_s, Q) as determinant sizes, and on the basis of theorem Π, we determined non-dimensional compounds (similitude criteria) for hammer mill grinding process, for physical sizes n and d_m :

$$\Pi_1 = \frac{n}{P^{x_1} {D_s}^{x_2} Q^{x_3}} \quad (2)$$

$$\Pi_2 = \frac{d_m}{P^{x'_1} {D_s}^{x'_2} Q^{x'_3}} \quad (3)$$

where exponents x_1, x_2, x_3, x'_1, x'_2, x'_3, were determined under the condition that Π_1 and Π_2 must be non-dimensional, in relation to the fundamental sizes L (length), M (mass), and T (time). So, the dimensional matrix of the five sizes in relation to the fundamental sizes L, M, T is given below:

	x1	x2	x3		
	P	**Ds**	**Q**	**n**	**dm**
L	2	1	0	0	1
M	1	0	1	0	0
T	-3	0	-1	-1	0

Under the condition that Π_1 and Π_2 must be non-dimensional in relation to the three fundamental sizes, the following equation systems were obtained:

$$\begin{cases} 2x_1 + x_2 = 0 \\ x_1 + x_3 = 0 \\ -3x_1 - x_3 = -1 \end{cases} \quad (4)$$

$$\begin{cases} 2x_1 + x_2 = 1 \\ x_1 + x_3 = 0 \\ -3x_1 - x_3 = 0 \end{cases} \tag{5}$$

Equation system for each parameter was resolved, then non-dimensional compounds became:

$$\Pi_1 = \frac{nD_sQ^{1/2}}{P^{1/2}} \tag{6}$$

$$\Pi_2 = \frac{d_m}{D_s} \tag{7}$$

For equations (6) and (7) regarding non-dimensional compounds, criterial equation under implicit form is:

$$\varphi(\Pi_1, \Pi_2) = 0; \varphi\left(\frac{nD_sQ^{1/2}}{P^{1/2}}, \frac{d_m}{D_s}\right) = 0 \tag{8}$$

Criterial equation under implicit form can cover other non-dimensional factors, like biomass moisture or other physical properties (non-dimensional). So, criterial equation becomes:

$$\Pi_1 = k{\Pi_2}^{\alpha_1} \tag{9}$$

meaning, that for this equation, solutions under the form of power produce is searched:

$$\frac{nD_sQ^{1/2}}{P^{1/2}} = k\left(\frac{d_m}{D_s}\right)^{\alpha_1} \tag{10}$$

from which it results into:

$$P^{1/2} = knQ^{\frac{1}{2}}D_s\left(\frac{d_m}{D_s}\right)^{-\alpha_1} \tag{11}$$

meaning:

$$P = k^2n^2Q{D_s}^2\left(\frac{d_m}{D_s}\right)^{-2\alpha_1} \tag{12}$$

thus, it can be expressed:

$$P = k_1\left(\frac{d_m}{D_s}\right)^{-2\alpha_1} \tag{13}$$

where k, k_1 and α_1 are coefficients that can be experimentally determined by direct recorded data regression analysis, and k_1 is expressed as:

$$k_1 = k^2n^2Q{D_s}^2 \tag{14}$$

Grading $-2\alpha_{1=}$ a, equation (13) becomes:

$$P = k_1 \left(\frac{d_m}{D_s}\right)^a \tag{15}$$

relation which can be used in regression analysis

Applying the same principle, from the criterial equation under implicit form, we can say:

$$\Pi_2 = k^* (\Pi_1)^{\alpha_2} \tag{16}$$

Thus, dependency relation of grinded particle dimension in relation to sieve orifice dimension is obtained:

$$\frac{d_m}{D_s} = k^* (\Pi_1)^{\alpha_2} \tag{17}$$

meaning:

$$d_m = k^* D_s \left(\frac{n D_s Q^{1/2}}{P^{1/2}}\right)^{\alpha_2} \tag{18}$$

or, getting back:

$$d_m = k^* D_s (\Pi_1)^{\alpha_2} \tag{19}$$

$$d_m = k_2 (\Pi_1)^{\alpha_2} \tag{20}$$

where:

$$k_2 = k^* D_s \tag{21}$$

and in which k^*, k_2, α_2 coefficients are constant coefficients, respectively exponents determined through regression analysis based on experimental data.

The Π Theorem states that if regression analysis does not lead to R^2 correlation coefficients with sufficiently high values, then the criterial equation under explicit form must be searched under a different form than power product.

3. Results and discussion

Experimentally obtained results regarding energetic biomass grinding are presented in tables 3 and 4. On the basis of table values, experimental power regression analysis on grinding necessary for the process according to Π_1 was realized, and also k_1 and α_1 coefficients were determined, from relation (15), for both biomass types and four hammer types used during experiments.

Thus, experimental coefficients of the rotor activation power equation for willow and Miscanthus, are presented in table 3.

$$P = k_1 \left(\frac{d_m}{D_s}\right)^a \tag{22}$$

On the basis of the same calculus principle, using experimental coefficients, experimental coefficients of explicit equation (15) for grinded particle dimensions were determined.

Table 3

Obtained experimental coefficients for rotor activation power equation

No.	Biomass type	Hammer type	k_1	a	α_1
1	*Miscanthus giganteus*	A	$4 \cdot 10^6$	-0.911	0.4555
2		B	13618	0.008	-0.004
3		C	54204	0.21	-0.105
4		D	177008	-0.382	0.191
5	*Salix viminalis*	A	891.74	0.398	-0.199
6		B	864.74	0.412	-0.206
7		C	32959	0.172	-0.086
8		D	1472	-0.273	0.1365

Grinded particle average size variation graphs were drawn, and regression analysis was again applied, using power type relation for both biomass types. Experimentally determined coefficients are presented in table 4.

$$d_m = k_2(\Pi_1)^{\alpha_2} \tag{23}$$

Table 4

Obtained experimental coefficients for grinded particle dimension equation

No.	Biomass type	Hammer type	k_2	k^*	α_2	R^2
1	*Miscanthus giganteus*	A	83.21	$(3.33–8.32)\cdot 10^3$	0.737	0.779
2		B	171.66	$(2.87-7.17)\cdot 10^3$	0.947	0.689
3		C	87.183	$(5.45-8.72)\cdot 10^3$	0.731	0.841
4		D	147.46	$(3.49-1.47)\cdot 10^3$	0.878	0.840
5	*Salix viminalis*	A	58.827	$(3.68-8.40)\cdot 10^3$	0.607	0.884
6		B	43.943	$(2.75-6.28)\cdot 10^3$	0.508	0.937
7		C	66.022	$(4.13-9.43)\cdot 10^3$	0.626	0.916
8		D	57.801	$(3.61-8.26)\cdot 10^3$	0.544	0.780

Just like we showed before, k_1 (from relations 14 and 22) depends on hammer rotor revolution speed, material feeding flow and sieve orifice diameter, directly proportional varying with the square of revolution speed and sieve orifice sizes, and just proportional with feeding flow. With values of k_1, values of k were calculated, with results between $(3.84\text{-}14.66)\cdot 10^3$ for type A hammer, between $(0.16\text{-}0.83)\cdot 10^3$ for type B hammer, between $(0.37\text{-}1.71)\cdot 10^3$, for type C hammer and between$(0.66\text{-}3.19)\cdot 10^3$, for type D hammer, for Miscanthus biomass grinding. For willow biomass grinding k values were between $(0.60\text{-}1.85)\cdot 10^2$ for type A, hammer. between $(0.60\text{-}2.10)\cdot 10^2$, for type B hmmer, between $(3.58\text{-}14.85)\cdot 10^2$, for type C hammer and between $(4.62\text{-}14.17)\cdot 10^2$, for type D hammer (see table 3). Also, exponent *a* leads to determining α_1, depending on grinded material characteristics (particle dimensions), but also by initial material particles, with high variation.

We can see that the smallest influence of k, on grinding necessary power is found in type B hammers, in the case of Miscanthus biomass, and type A hammers, in the case of willow biomass.

In figure 1 grinded particle dimension variation curves in relation to Π_1 non-dimensional compound are presented, obtained through regression on the basis of relation (22) and experimental data, for willow biomass. Obtaining a relatively high value correlation coefficient can be seen, which solidifies proposed model validity.

It is also observed (from the graphs and in Table 2) that the smallest dimensions of the crushed particles are obtained in the case of the two-edge hammers, followed by the one- and three-edge hammers, regardless of the revolution speed, the material feed rate and the diameter of the orifices of the sieve.

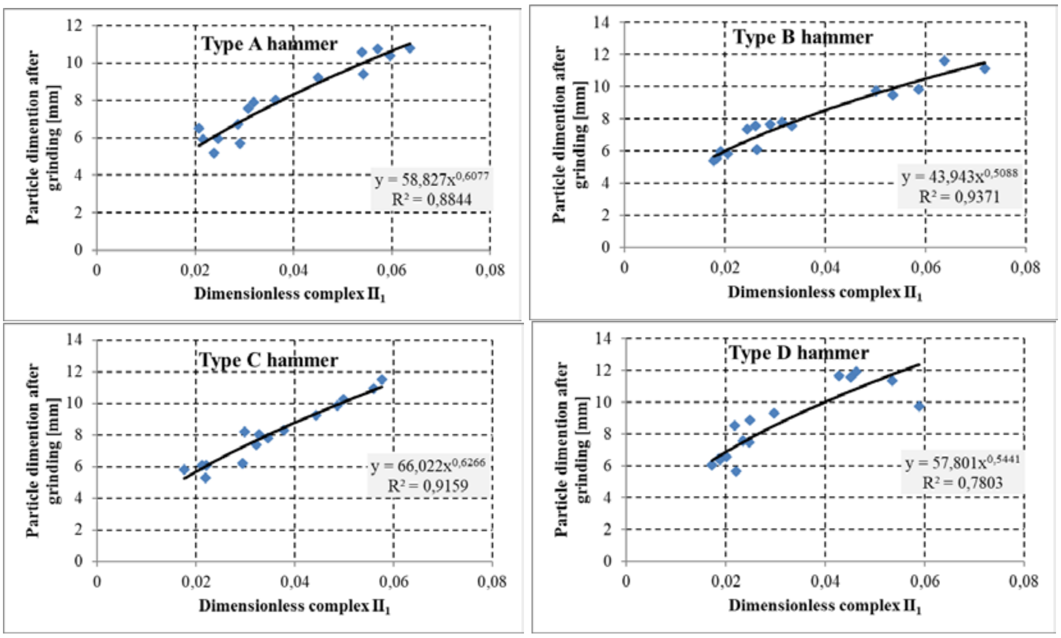

Fig.1 Grinded biomass particle dimension variation with Π_1 non-dimensional compound

Same as before, k_2 coefficient (from relations 20, 21 and 23) depends on sieve orifice dimensions, being directly proportional with them. Knowing values of k_2, values of k* were determined (rel.21), and were between (3.33–8.32)·10^3 for type A hammers, (2.87-7.17)·10^3, for type B hammers, (5.45-8.72)·10^3 for type C hammers and between (3.49-1.47)·10^3 for type D hammers, in the case of Miscanthus biomass and between (3.68-8.40)·10^3 for type A hammer, (2.75-6.28)·10^3 for type B hammers, (4.13-9.43)·10^3 for type C hammers and between (3.61-8.26)·10^3 for type D hammers, in the case of willow biomass. We can see that sieve orifice dimensions have a strong influence on k*, also on grinded particle dimension, d_m. Regarding exponent α_2 size, it has a smaller influence as its value gets closer to 1, which happens in the case of type B hammers, for Miscanthus biomass (see table 4).

Dimensional analysis theory was also applied for many variants, with 6 and 7 main parameters, that influence hammer mills working process, but obtained results were not the anticipated ones at the start of the non-dimensional calculus.

4. Conclusions

Physical processes with multiple influencing factors, which can't always be quantified, can be theoretically modelled through dimensional analysis and similitude theory.

Our paper analyzed, both experimentally, as well as theoretically, hammer mills working process, used for Miscanthus and willow biomass grinding, using special harvesting pre-grinding machines.

Both experimental, as well as theoretical observations, prove that the main influence on hammer mill energy consumption is given by hammer rotor speed, power rising proportionally with its square, but also feeding flow for which necessary power varies also proportionally, as well as sieve orifice diameter, as it can be seen from non-dimensional compound relations determined in the paper.

Also, mathematical model exponents and coefficients, presented for grinding necessary power and grinded particle dimensions, depend greatly on the constructive hammer type in hammer mills, meaning the number of edge corners with which they attack material particles during working process.

Due to hammer mill process parameters variability we proposed mathematical expression for power and grinded particle dimensions (as grinding estimating indices) on the basis of the mathematical model resulted from dimensional analysis of process parameters and experimental data synthesized in the paper.

The mathematical model proposed in this paper can be used for fast prediction of grinding miscanthus and willow biomass energy consumption, when the initial and final particle dimensions are known. Moreover, it can constitute the base of further developing of other mathematical models which take into consideration more parameters that interfere in the grinding process using hammer mills.

5.Aknowlwdgements

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