POLITEHNICA UNIVERSITY OF BUCHAREST
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Summary of PhD Thesis

CERCETĂRI PRIVIND OPTIMIZAREA PROCESULUI DE MĂRUNȚIRE A BIOMASEI CU AJUTORUL MORILOR CU CIOCANE

RESEARCHES REGARDING BIOMASS GRINDING PROCESS OPTIMIZATION USING HAMMER MILLS

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SUMMARY

Preface

The thesis is structured on 7 chapters, developed on 174 pages, illustrated with 149 figures, 44 tables, 211 mathematical relations, as well as a bibliography composed out of 107 bibliographical sources. Also, the thesis contains a series of annexes (approximately 38 pages).

The doctorate thesis “Researches regarding biomass grinding process optimization using hammer mills” presents a synthesis of experimental researches made by the author regarding the energetic plant grinding process and the implications of different constructive and functional paramenters on the working regime. The mail objective of the experimental researches from this thesis is the energetic plant biomass grinding process using hammer mills, a process that’s a part of the technological process for obtaining solid bio-fuels.

In the paper’s chapter 1, general elements referring to the importance of using biomass for solid bio-fuels production is presented, as well as the necessity of following preparation processes regarding a more reliable manoeuvrability.

Chapter 2 presents general considerations regarding biomass grinding from energetic plants, through presenting aspects of physical-mechanical energetic plant biomass properties.

In Chapter 3, entitled **“Actual state of theoretical and experimental researches regarding working process and hammer mill construction used for biomass grinding”**, hammer mills constructive solutions, types of hammers and their rotor distribution, as well as a synthesis of worldwide theoretical and experimental researches on hammer mill working process are presented.

Chapter 4, entitled **“Theretical aspects and contributions regarding the working process of hammer mills”,** describes, in the beginning, theoretical aspects regarding hammer shock equilibration and rotor dinamic equilibration. Also, in chapter 4, the mathematical modelling of hammer mills working process was realized, through dimensional analysis using Π theorem, as well as the simulation of stresses on the hammer mills working organs, using SolidWorks 2016 Premium software.

In chapter 5, entitled **„Experimental researches regarding grinding equipment working process using two types of biomass”,** in the beginning, devices and working methodology regarding experimental determinations is presented. Also, it gives reference to appreciation indices of the grinding process resulted through research realization.

Chapter 6, entitled: **“Contributions regarding biomass grinding process optimization using hammer mills”**, outlines aspects regarding correlations between grinding process describing parameters, an optimization study on the one-edge corner hammer, a regression analysis for the energetic function, objective functions that describe working process quality for hammer mills, but also quality static modelling through Rosin-Rammler distribution.

Chapter 7 is designated for **General conclusions** of the paper and personal contributions regarding the optimization process for biomass grinding using hammer mills. Also, perspectives regarding this theme, that cn be approached furthermore by other researchers, are outlined.

The author considers this thesis is a relatively modest contribution regarding the optimization process for grinding biomass, using hammer mills.

List of symbols and notations

Chapter 2 – General considerations regarding energetic plant biomass grinding

m	material probe mass (kg);
Z	degree of grinding (mm);
D	average equivalent dimension of feed material (mm);

Chapter 3 – Actual state of theoretical and experimental researches regarding working process and hammer mill construction used for biomass grinding

D_m	hammer rotor diameter (m).
L_m	hammer rotor length (m).
Q	material feed flow (kg/s);

Chapter 4 – Theretical aspects and contributions regarding the working process of hammer mills

a	hammer length (m);
b	hammer width (m);
c	distance from hammer articulation axis to its center mass (m);
f	distance from the fixture holes center to the hammer edge (m);
l	level which indicates the fixture hole center to the hammer tip;

Chapter 5 – Experimental researches regarding grinding equipment working process using two types of biomass

R(x)	refusal on the x orifice diameter sieve x (%);
x	average dimension of particles (d) class (μm or mm);
b, n	constant coefficients or distribution parameters experimentally determined through regression analysis.

Chapter 6 – Contributions regarding biomass grinding process optimization using hammer mills

d_s	sieve diameter (m);
ν	speed (rotation frequency) of the rotor (s^{-1});
t	batch processing time (s).

Chapter 1- Introduction. Thesis importance and objectives

Experimental researches realized by scientists lead to the conclusion that biomass resources can be transformed into any form of energy. Biomass, subjected to different preparation processes rom the technological flow leads to different finite products destined for consumers. But the costs are heavily influenced by the overall costs of technological flow processes, so researches are researching optimization for each stage, with the objective to lower energy consumption, to prolong lifespan of the equipment used, and to enhance the quality of the final product.

This paper's main objective refers to the biomass grinding process optimization using hammer mills. Out of the specific objectives from this thesis we can add:

- identifying factors that influence the energetic plant grinding process (biomass);
- study of the biomass grinding equipment construction, especially of hammer mills;
- theoretical study of the hammer mill working organs process;
- mathematical modelling of the hammer mill working process;
- simulation of the stresses inside hammer mill working organs;
- determining hammer type influence on the grinding degree of energetic plants;
- determining hammer rotor speed on the grinding degree of energetic plants;
- determining sieve dimension influence on the grinding degree of energetic plants;
- establishing correlations between hammer mill grinding process parameters, with the purpse of efficiency enhancement.

Chapter 2. - General considerations regarding energetic plant biomass grinding

2.1 Synthesis of physical-mecanical properties of energetic plant biomass

Although modern industry constant development regarding the use of energetic plants is astonishing, physical-mechanical and chemical basis material properties are less known. In the paper, biomass properties like: particle density, volumic mass, porosity, tightness, humidity, mechanical resistance, elasticity module, grinding specific energy, plant caloric power, biomass chemical composition, are presented.

2.2. Grinded material requirements for pelletizing/ briquetting use

The most important compaction process variable is the material composition (biomass). The compaction process is heavily influenced by the biomass physical-mechanical properties and by the binders used. The grinding degree obtained following the grinding process contributes to technological process quality determination and to the market commercialized product.

2.3. Theoretical bases of grinding operation and appreciation indices

Optimum grinding operation represents the transformation of a material with a low consumption into a product with certain granulometric conditions demanded by the next operation from the working flow. For characterizing a grinding process, it is necessary to know the three main indices: grinding degree, Z; grinded material module, M; specific energy consumption, L_s. The necessary energy for the grinding process depends on the biomass nature, its initial state (distribution by dimension), its structure and its internal state, size, speed and effort for the applied effort. In the limits of elastic deformations, it is assumed that the entire energy is consumed for biomass particle deformation, and so, the specific mechanical work is proportional with the deformed volume (raport between initial and final volume), [14].

The majority of experimental relations can be drawn starting from the next general equation:

- **general equation for energy:**

$$dE = -C\frac{dD}{D^n} \tag{2.27}$$

In order to integrate this equation between the d and D limits, and giving different values to n, we obtained Kick, Rittinger, Bond, Gross-Zimmerley laws for obtaining the consumed energy values for energetic plant grinding.

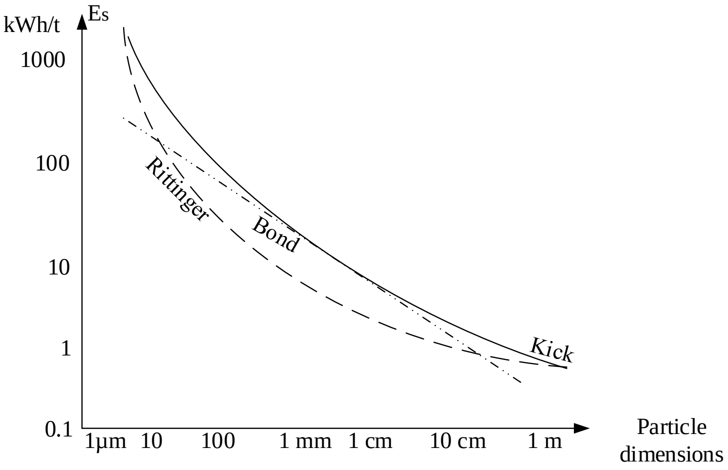

Fig. 2.3. Specific grinding mechanical work in relation with particle size [68]

2.4. Conclusions regarding energetic plant biomass grinding

The grinding operation contributes to an easier biomass handling and to realizing a cimpact finite product, destined for end users. In order for the crops grinding to be realized with an optimum energy consumption, in the speciality literature, we can find studies and researches that seek grinding equipment ehnahcements, both from a design point of view, as well as for fulfilling the grinded material working processes requirements after this stage.

Chapter 3. - Actual state of theoretical and experimental researches regarding working process and hammer mill construction used for biomass grinding

A series of mechanical equipment used for the energetic plant biomass grinding are presented in this chapter. Out of these we can outline: the closed chamber hammer mill MCE-1, the open chamber mill MC-3, the hammer mill Champion 11, the hammer mill Moinho de Martelo, the hammer mill Peruzzo, Optimill, Agrobi Richet, Mill 800, WCR. Also, inside this chapter, the main elements of a hammer mill are presented: hammer rotor, hammers, sieves. After this, aspects regarding worldwide theoretical and experimental researches are presented.

3.1. Constructive solutions synthesis for vegetal biomass grinding

Advantages of hammer mill lie in the possibility of use for raw, average, and fine grinding, obtaining a high grinding degree, with a linear energy consumption, if the hammer mill flow is taken into consideration. An example for this is the open chamber hammer mill MC-3, presented in figure 3.2, and in parallel we can see the mill's working organs.

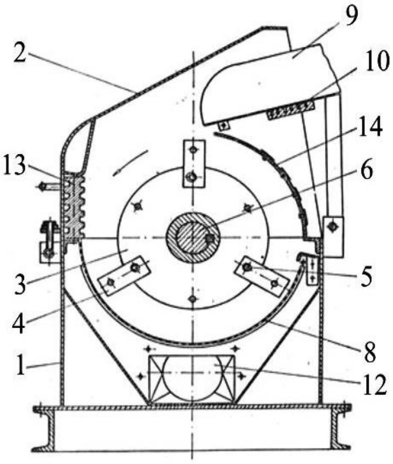

Fig. 3.2. Constructive layout of the open chamber hammer mill MC - 3 [14, 55]

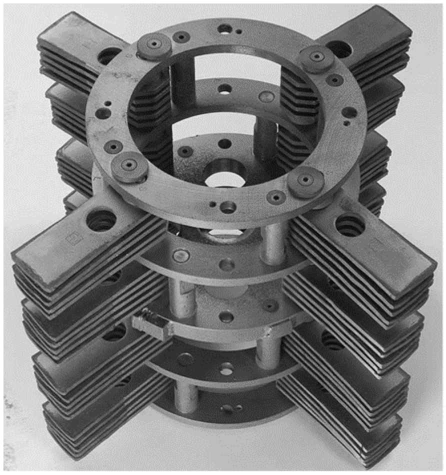

Fig. 3.19. Hammer mill working organs [103]

Width of the grinding chamber is 310 mm and the hammer rotor diameter is 520 mm, at a sieve wrapping angle of 180°. The mill rotor is equipped with 10 discs (3), 54 hammers (4), mounted on three axes (5) staggered at 120°. The hammers are mounted 18 on each axe, two hammers on each interval between two discs. The distance between hammers is determined by three collars of 3, 6 and 9 mm thickness, which ensures a combined distribution of the hammers on the rotor. Under the rotor, there is an interchangeable sieve (8) which ensures the wanted grinded material dimension. The feeding device is formed by the chamfer (9) and the permanent magnet box (10), which has the role to retain ferrous impurities. Material feeding is tangentially achieved through free flow on all the grinding chamber length, through chamfer (9) inclination. During entrance in the grinding chamber, the material particles are subjected to hammer hits. Due to these hits, initial particles are crumbled, and the resulted particles are projected on plates (13) and (14), where a second grinding takes place. From these plates, the resulted particles bounce and reach again the area of hammer hits, after which the phenomenon repeats itself. Particles that have reached the dimensions of the sieve's orifices pass through and are evacuated through the transportation pipe (12).

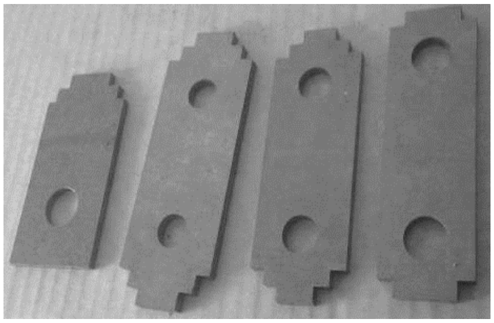

Fig. 3.15. Constructive forms of hammers [14]

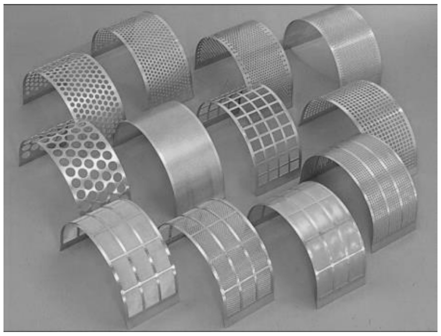

Fig. 3.21. Different types of sieves used for grinding biomass [104]

Hammers represent the mail working organ of hammer mills. Their constructive form. greatly influence the quality of grinded material and the specific energy consumption.

The second working organ used during the grinding process is the concave. This can be cylindrical, semi-cylindrical, or under the form of cylindrical sectors, with a surface of different forms: riflated, toothed, or with orifices. In some cases the concave is missing, and its role is taken by the sieve. The role of the sieves is to separate the grinded material from the grinding chamber. The separation capacity depends on the dimension and orifice density on 1 cm^2, the type of orifices and the space occupied on the sieve on the grinding chamber contour.

Also, an importan element of hammer mills that must be mentioned is the shape of the hammer rotor. In order to determine the main hammer rotor dimensions, it is necessary to know the grinding capacity, grinded material granulation, material physical-mechanical properties.

3.2. Worldwide theoretical and experimental researches regarding the working process of hammer mills

In the synthetic analysis of these researches, the study of the hammer mills working process and the influence of the material on functioning parameters during experimental researches was researched. Inside a hammer mill, grinding takes place through impacts with the material and its fragmentation. Rsearches regarding hammer mills have been done especially for grinding speed, work flow, sieve orifice size, grinded material evacuation. Hammer mills are used for grinding average or fine size materials because the process of grinding consumes less energy.

A high energy consumption for grinding process was outlined for energetic grass, no matter the size of the sieve's orifices or material's humidity content. An energy consumption of 51.6, 37.0, respectively 11.4 kWh/t was recorded for sieves with orifices of 0.8, 1.6 and 3.2 mm and strawlike biomass humidity was between 4 and 7%. Analyzing corn stalks, consumed energy was of 11 kWh/t for the 3,2 mm sieve, and 12% humidity for material probes [55]. Researchers concluded the fact that the consumed energy during grinding process is greater for smaller sieve orifice sizes, [55].

Mani et al (2003), [36], studied the effects of rice and wheat straws, corn stalks and Miscanthus on a hammer mill, where sieves of 3.2, 1.6, 0.8 mm were used. Following data analysis, corn stalk pellets that were grinded using the 1.6 mm sieve were 5 to 16% denser that the pellets obtained from grinded biomass using 3.2 mm sieve.

Murphy et al [49], observed, through experimental testing, that reducing the dimensions of the sieves from 3 mm to 2 mm resunted in a shrinkage of grinded particles for wheat, sorghum and rice. The energetic consumption for the grinding process of palm seeds and nut peels were analysied using a laboratory hammer mill. The type of material and the sieve used heavily influenced the energy consumption [37]. Relations between the energetic consumption and the sieves used showed a polynomial form. Bulk density of nut peels dropped due to a rise in average diameter, and in the case of palm seeds, bulk density got higher due to average diameter.

In another study, experimental researches, similar to this one, were achieved using hammer mills. Reducing Miscanthus, switchgrass, willow, and reed biomass size reduction was researched. Grinding equipment were a knife mill Retsch SM200, a hammer mill Retsch SK100 and a commercial hammer mill. Experimental results showed a dependency between energy consumption during grinding and sieve orifice sizes, exemplified through the laws used for experimental data processing. Particle dimensions after grinding were demonstrated to be reverse propoportional to the particle density for each of the four types of biomass.

A conclusion for experimental researches showed a power type function for the grinding energy consumption dependency on the sieve orifice dimensions. It was shown that for the same sieve orifice sizes, the hammer mill was more efficient than the knife mill. Shastri et al. [58] analyzed the problem of biomass grinding and densification in order to optimize the process and to reduce energy consumption. Results obtained following experiments in the grinding process for Miscanthus showed that both bulk density and soecific energy consumption lowered due to a larger particle size [58].

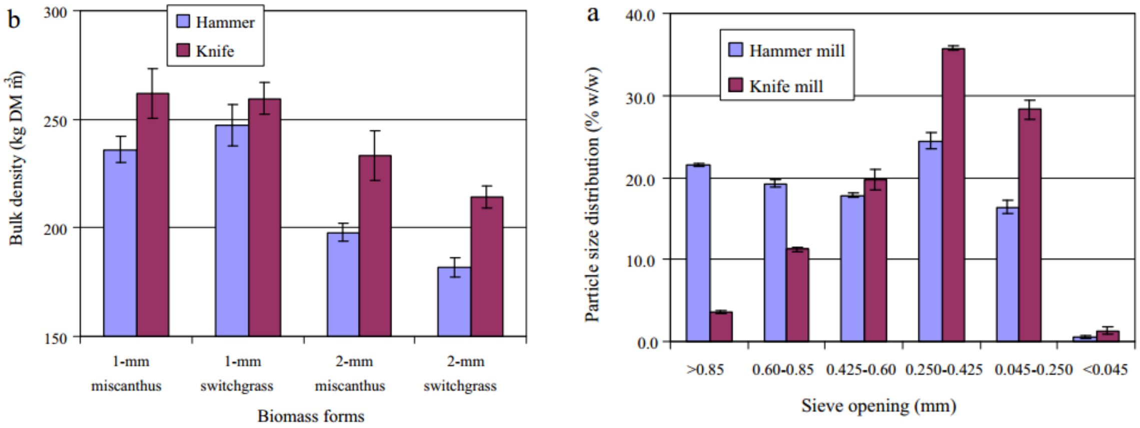

Fig. 3.34. Comparing volumic mass according to Miscanthus and switchgrass particle dimensions on the hammer mill Retsch SK100 and SM2000 [42]

Experimental data for grinding Miscanthus stalks showed that the volumic mass was inversely proportional with the particle size. Experimental researches were conducted using: 4 different speeds: 1550, 1800, 2000 and 2250 rpm, 3 levels of material humidity 10, 12 and 14%, and three types of hammer thickness: 1, 3 and 5 mm.

A rise in rotor speed lead to a rise in mill capacity, but a drop in energy efficiency. The best value for the mill capacity was 0,871 Mg/h, obtained at 2250 rpm, 10% humidity and 5mm hammer thickness, whilst the best energetic efficiency (92,9%) was obtained at 1550 rpm, 14% humidity, and 1,5 mm hammer thickness [107].

From an economic point of view, in the case of a pellet production line, only the pellet press consumes more energy than the grinding biomass hammer mill, regarding total energy consumption. For a finer grinding, both consumed energy and active organs wear are more accentuated.

3.3. Conclusions regarding theoretical and experimental researches state

From the hammer mill constructive solution analysis, we can say that hammer mills did not suffer significant changes from a working process point of view, but constructively, they have become more efficient. An important element that helps consumers today is linked to hammer mill sizes. Due to their size, these mills can be used both in private establishments, and in different materials industrial processing lines.

Also, from studies realized with the purpose of determining the behavior of plants during grinding/milling process, the fact that the plants mechanical properties, strongly influence the equipment working process.

Statistically, a hammer mill energetic consumption during its lifespan is about 10 to 20 times higher than the initial equipment price. For hammer mills, a higher yield is given by choosing sieves that are in accordance with the electric motor power, with which the mill has been equipped. Also, the peripheric speed is very important, having a significant influence on biomass particle dimensions after the grinding process.

High peripheric speeds (5000 rpm) will lead to finer particles than smaller peripheric speeds (2000 rpm). As a rule, sieves with smaller orifices should be used for high peripheric speeds, whilst sieves with large orifice sizes should be used for small peripheric speeds. Hammers osed on hammer mills are highly diversified, in Europe, the most common are the plane ones with two holes with no edge treatment [34].

Chapter 4. - Thoeretical aspects and contributions regarding the working process of hammer mills

4.1. Aspects regarding hammer shock equilibration and rotor dynamic equilibration

In desing and construction of hammer mills used for biomass grinding, an important problem is determining the hammer rotors constructive paramenters. The constructive parameters if the two components have an important influence on mill functioning. Choosing the right parameters ensures a reduced vibration workflow which contributes to a rise in exploitation time.

In order for the exploitation time to pe prolonged, certain material feeding conditions are adopted, and a stable hammer movement in the grinding process is ensured, mill rotor is equilibrated both from a static and dynamic point of view.

Through hammer shock equilibration, adoption of such material feeding and choosing some hammer constructive parameters are realized, so that applied percussions on the particles by the hammers are not transmitted to O_1 joint. For analyzing the hammer mill's equilibration parameters, the MC-22 hammer mill was chosen, and it was studied from a hammer shock equilibration point of view.

The condition for hammer shock equilibration is achieved if the percussion that appears in its joint is null. According to speciality literature [14, 74], the tangential component of these percussions is null, when the hammers strike the material perpendicular. In order for this to be achieved, material feeding into the mill is usually done on a tangential direction. Considering that percussions are applied to hammer periphery, the normal percussion component is equal to zero only if the hammer l length satisfies the relation:

$$l = \frac{J_{O_1}}{M \cdot c} \tag{4.27}$$

where: J_{O1} is the hammer inertia moment in relation with its joint axis (kg m2); M – hammer mass (kg); c – distance from the hammer joint axis to its mass center (cm). Each time, values of l, c, J_{O1}, M and f were calculated, starting from the known values of hammer length a, hammber width b, fixture hole and edge dimensions for each hammer corner. It was concluded that there are quite large differences between J_c and J_{01} (towards the hammer mass center and towards the rotor joint point), according to the corners geometric form and action on the material. It is mandatory that all corners respect execution prescriptions in order to avoid differences of shape that could lead to an ununiform functioning. Regarding f hammer shock equilibration level, we concluded that the calculated values are very different than their real value, which meant that the constructor did not respect theoretical requirements. This can induce a vibration packed functioning that can shorten the estimated lifespan of the mill.

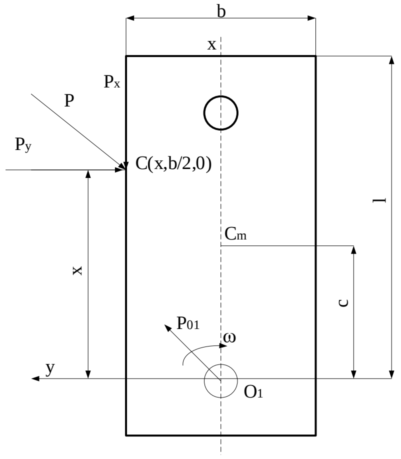

Fig 4.3. Calculus schema for hammers shock equilibration

For MC-22 mill hammer shock equilibration, 4 types for hammers, with different edges were chosen, but with identical general dimensions.

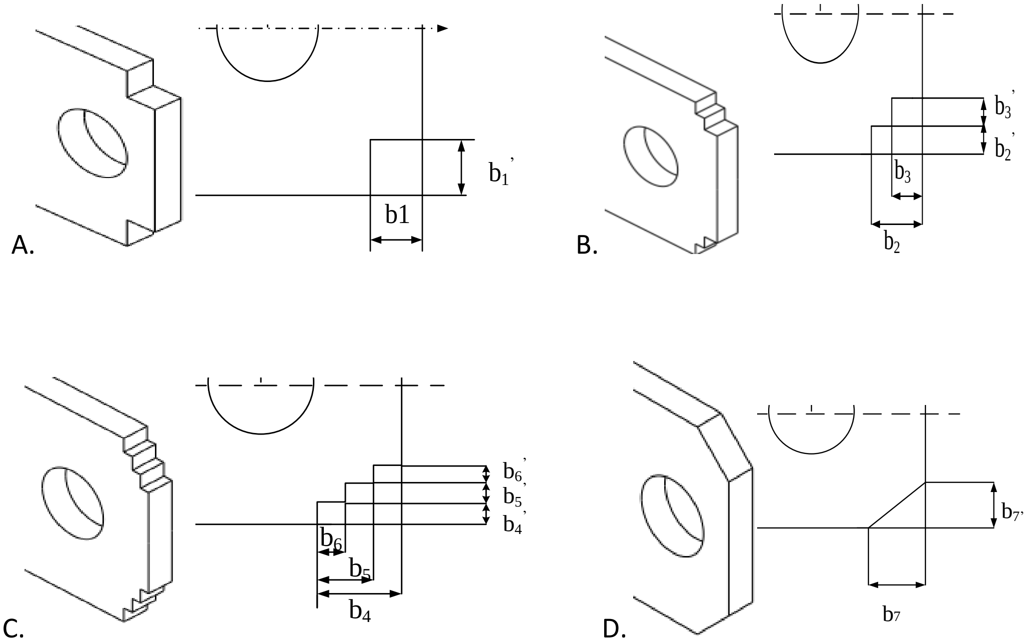

Fig. 4.6, 4.7, 4.8, 4.9 Types of hammers analyzed for shock equilibration

In order to talk about rotor equilibration conditions, we must first talk about hammer distribution on the rotor and the way this influences the process. In order for the rotor to be in equilibrium, it is necessary that the correct hammer distribution achive certain conditions like: on the same path a minimum number of hammers should pass, preferable 1, to not crowd the material in a certain area of the grinding chamber and the hammers should cover the entire working area. In general, dynamic equilibration is achieved if the hammers have a symmetrical distribution throughout the rotor. The disadvantage of distributing the hammers following helical lines is given by the fact that it crowds the biomass in one of the grinding chamber's areas. Knowing hammer distribution on the rotor, hammer thickness of 8 mm and disk thickness of 10 mm, inertia momentum variation diagrams were drawn, on the two axis according to the rotation angle.

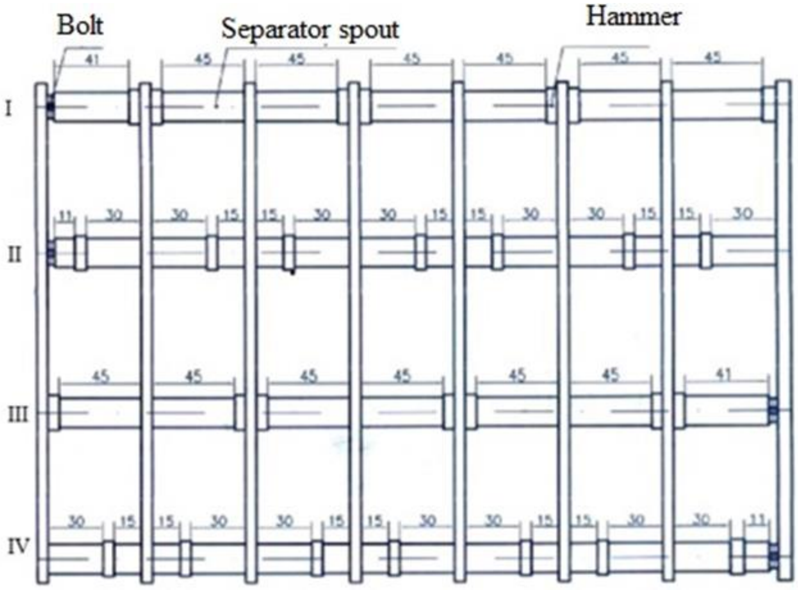

Fig. 4.13 Hammer distribution on the rotor [10]

Figure 4.15 represents the inertia moment in relation with the rotor rotation angle. We can observe a sinusoidal curve with positive and negative values, the inertia moment being between $2 \cdot 10^{-3}$ and $-2 \cdot 10^{-3}$ ($kg \cdot m^2$).

From what can be observed in figure 4.15, the two inertia moment curves Izx and Izy never pass simultaneously through zero. Also, the maximum value is the same for both inertia moments, maximum and minimum values for Izx and Izy being relatively small.

Also, for certain positions the inertia moment on Oy axis is 0 and the inertia moment on OX axis is either maximum or minimum and reversed. These values of the centrifugal inertia moment can introduce some rotor vibrations in relation to Oz axis (on the rotor's length).

Hammer rotor equilibration is very important for a better hammer mill functioning, without vibrations. Our verifications for the Romanian MC-22 hammer mill lead to two major conclusions: the hammers are not shock equilibrated (there is a large difference between calculated f and real f of about 47 mm at 10 mm); there is a small value of centrifugal inertia moments, different to zero (for levels from the hammer distribution on the rotor drawing).

Any deviation from the hammer geometry and from its mass introduces a new disturbance during hammer rotor spin, which leads to a vibration packed functioning, no matter how small the deviations are. Any deviation from the hammer distribution dimensions on the rotor (throughout the joint bolt), also introduces new rotor disturbances, leading to more vibrations. Any deviation from the angular position, no matter how small, of the joint bolts, will also lead to more vibrations due to rotor poor equilibration.

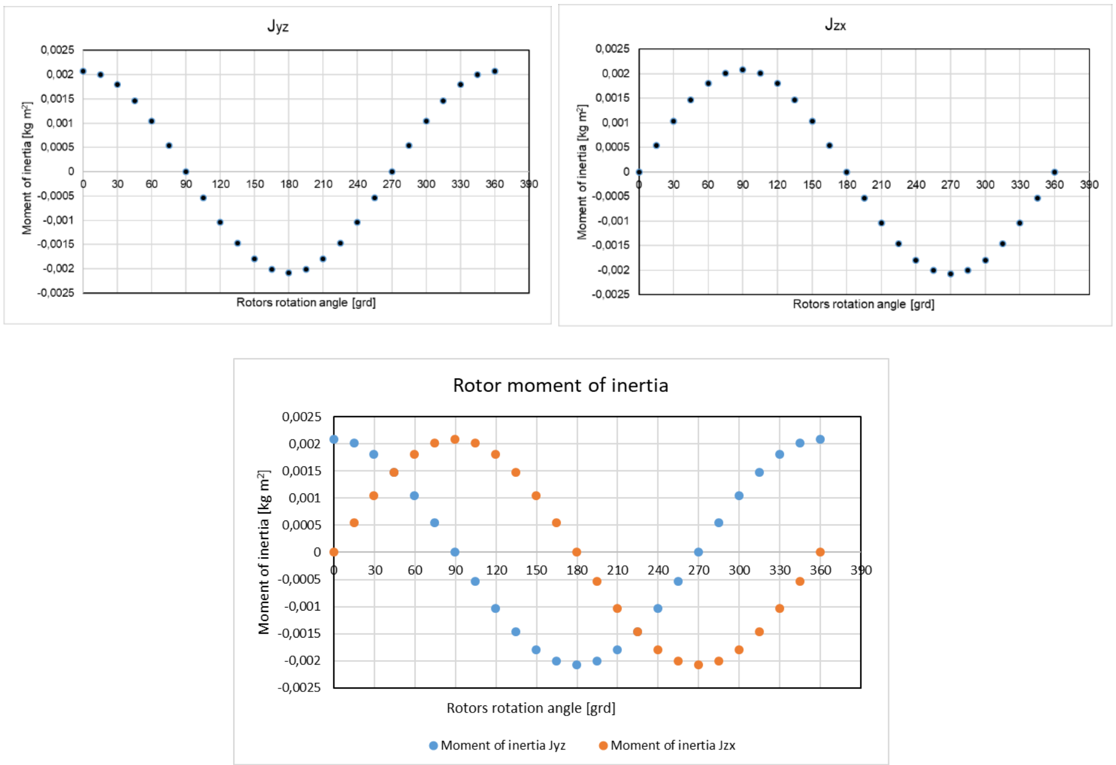

Fig. 4.15. Inertia moment variation [45]

a. Inertia moment variation on Ox axis; b. Inertia moment variation on Oy axis

4.2. Hammer mills working process mathematical modelling, through dimensional analysis, using theorem II

In order to study biomass grinding process using hammer mills, the theory of dimensional analysis was applied, with the purpose of mathematically modelling this process. Through this analysis, anticipating the necessary mill auctioning power for grinding Miscanthus biomass and energetic willow was researched. Mathematical modelling was realized through dimensional analysis using theorem Π, stated by Buckingham, [65, 71].

Only 6 main parameters that influence thw hammer mill working process were taken into consideration for analyzing the hammer mill working process: consumed power during working process P ($kg\cdot m^2/s^3$), hammer mill consumed energy E (m^2/s^2), particle size after grinding d_m (m), hammer mill speed, n (s^{-1}), hammer mill sieve orifice sizes D_s (m), feeding flow Q (kg/s). Also, we considered an analysis with 7, respectively 5 main parameters that influence hammer mills working process.

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

$$f(E, P, D_s, Q, n, d_m) = 0 \tag{4.97}$$

It was considered that group (E, P, D_s) had determining sizes, and on the basis of theorem π, adimensional compounds were determined (similarity criteria) of the hammer mill grinding process for physical sizes n, Q, d_m:

S-a considerat ca mărimi determinante grupul (E, P, D_s), iar pe baza teoremei π, s-au determinat complecșii adimensionali (criteriile de similitudine) ai procesului de mărunțire al morilor cu ciocane pentru mărimile fizice n, Q, d_m:

$$\Pi_1 = \frac{Q}{P^{x_1}E^{x_2}{D_s}^{x_3}} \tag{4.98}$$

$$\Pi_2 = \frac{n}{P^{x_1'}E^{x_2'}{D_s}^{x_3'}} \tag{4.99}$$

$$\Pi_3 = \frac{d_m}{P^{x_1''}E^{x_2''}{D_s}^{x_3''}} \tag{4.100}$$

in which exponents x_1, x_2, x_3, x_1', , x_2', x_3', x_1'', x_2'', were determined out of the conditions that π_1, π_2, și π_3 should be adimensional, in relation to fundamental sizes L (length), M (mass), T (time). Thus, the dimensional matrix of the 6 sizes in relation to L, M, T fundamental sizes is described below:

	x_1	**x_2**	**x_3**			
	P	**E**	**D_s**	**Q**	**n**	**d_m**
L	2	2	1	0	0	1
M	1	0	0	1	0	0
T	-3	-2	0	-1	-1	0

Putting the condition that Π_1 must be adimensional, in relation to the three fundamental sizes L, M, T, from the upper matrix, the following system of linear equations was obtained:

$$\begin{cases} 2x_1 + 2x_2 + x_3 = 0 \\ x_1 = 1 \\ -3x_1 - 2x_2 = -1 \end{cases} \tag{4.101}$$

Resolving the system solutions were produced $x_1 = -1$, $x_2 = -1$, $x_3 = 0$, respectively $x_1' = 0$, , $x_2' = 1/2$, $x_3' = -1$ respectively $x_1'' = 0$, , $x_2'' = 0$, $x_3'' = 1$ so the expression of the adimentional compound Π_1 Π_2 respectively Π_3 becomes:

$$\Pi_1 = \frac{Q}{PE^{-1}} = \frac{QE}{P} \tag{4.102}$$

$$\Pi_2 = \frac{nD_s}{E^{1/2}} \tag{4.104}$$

$$\Pi_3 = \frac{d_m}{D_s} \tag{4.106}$$

With these adimensional sizes, the implicit form criterial equation was obtained:

$$\varphi\left(\frac{QE}{P}, \frac{nD_s}{E^{1/2}}, \frac{d_m}{D_s}\right) = 0 \tag{4.107}$$

For determining the hammer mill working process necessary power, the P term from the criterial equation was separated, becoming:

$$\frac{QE}{P} = \varphi\left(\frac{nD_s}{E^{1/2}}, \frac{d_m}{D_s}\right) \tag{4.108}$$

For a first approximation the mathematical model of power produce from the other adimensional sizes was proposed, respectively:

$$\frac{QE}{P} = k^{*}\left(\frac{nD_s}{E^{1/2}}\right)^{\alpha_1}\left(\frac{d_m}{D_s}\right)^{\alpha_2} \tag{4.109}$$

in which: k^{*}, α_1, α_2, are constant coefficients, respectively calculated exponents through linear regression based on experimental data. Doing the calculations and separating hammer mill auctioning power, the equation becomes:

$$P = \frac{1}{k^{*}}\, QE^{1+0,5\alpha_1} n^{-\alpha_1} D_s^{\alpha_2-\alpha_1} d_m{}^{-\alpha_2} \tag{4.110}$$

For dimensional analysis with 5 parameters, the grinded biomass particle dimension variation with the adimensional compound Π_1.

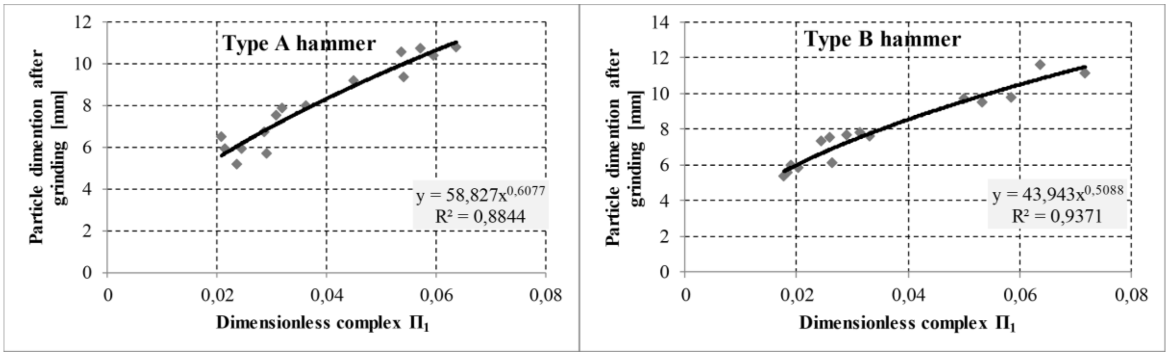

Fig. 4.17. Grinded biomass particle dimension variation with the adimensional compound Π_1

4.3. Simulation of stresses inside hammer mills working organs

During this stage of the thesis, the finite element method (FEM) was applied for the structural analysis of hammer mill's working organs. For hammer mill working process simulation, SolidWorks 2016 Premium software was used, which allows both the design and resolving difficult tasks in a fast and efficient way. The first phase of this modelling was generating the geometric model followed by generating the meshed model. Working organs geometry was realized using SolidWorks, and its represented in figure 4.18. Working organs were created starting from the known disk dimensions, hammers and rotation axle. For applying the complications of movement and simulation, an ansamble of 2 disks and 4 hammers was chosen.

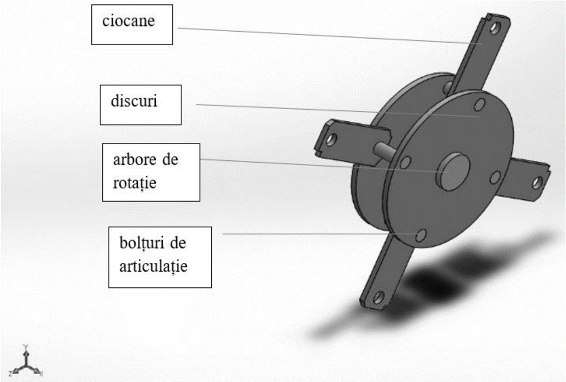

Fig. 4.18. Geometric model for the ansamble

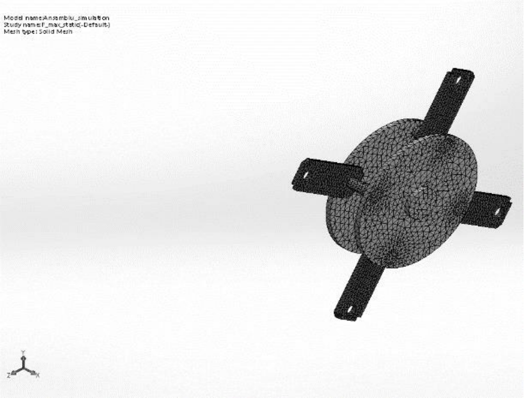

Fig. 4.22. Meshing in tetrahedral finite elements for the model

Rotor speed for analysis was chosen to have the value of 3000 rpm. A rotor stabilization from start until maximum speed was observed in just 1,2 seconds. From the resulting graphs, we could observe a hammer oscillation stabilization after 2 seconds (fig. 4.19). The number of frames per second was established at 12000.

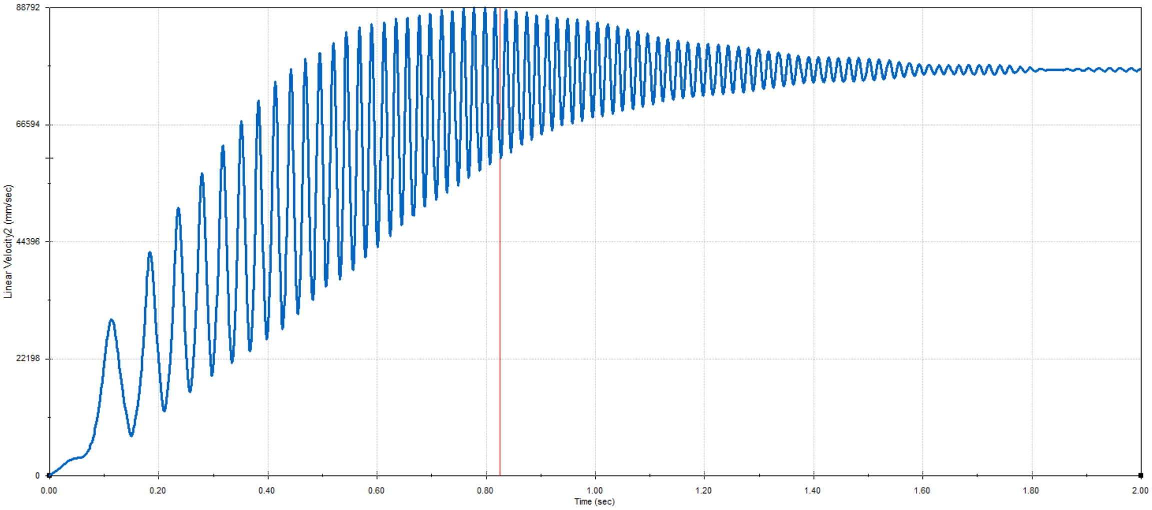

Fig. 4.21. Peripheric variation speed for one of the rotor's hammers.

A static analysis was realized from which the movements, tensions, as well as inherent frequencies were resulted. In the case of static analysis, the subjected material breaks in the place in which calculated efforts overcome the material breaking limit. Frequency analysis was realized for identifying if there are inherent frequencies that coincide with the rotor functioning frequency or if they are smaller than it. It was observed that the main ansamble frequency is 33903 rad/s, a value much superior to the rotor functioning frequency of 314 rad/s.

From inherent frequency analysis results obtained, a maximum deformation of 0,036 mm could be observed at the tip of the hammers, due to centrifugal force during functioning.

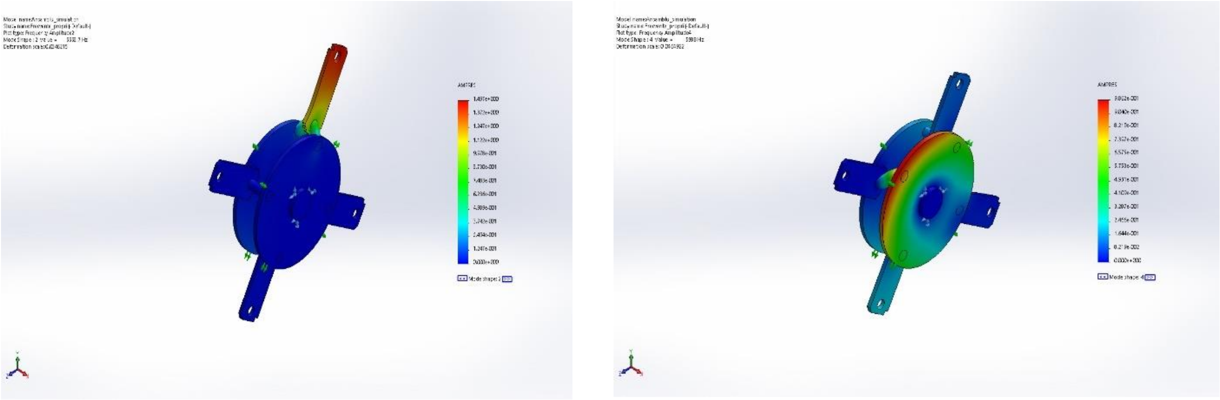

Fig.4.24. Ansamble deformation through applying frequency analysis for different inherent frequencies

4.4. Conclusions regarding hammer mills working process

Reffering to hammer shock equilibration we could identify that due to some identical hammer dimensions for type A, B, C and D, the calculated values fo l, c, and f are also identical.

Also, small differences between the three values of f level were observed (f level indicates hole position and represents the hammer shock equilibration level). Through finite element simulation a maximum deformation of 0,036 mm at the hammer tip could be observed, due to centrifugal force during functioning. Also, tensions were half of the elasticity limit, and the equivalent unitary effort is manifested on the contact surface of the hammer for each hammer with every axle.

Chapter 5. - Experimental researches regarding grinding equipment working process using two types of biomass

5.1. Objectives of experimental researches and utilized equipment

Experimental research general objective from the current paper is the grinding mechanical processing analysis from the solid biofuel general technological process, and its purpose is enhancing performance for the equipment that are used for these operations and establishing new optimum working regimes for the grinding machine.

Out of this thesis, we can outline the following specific objectives:

- identifying factors that influence the energetic plant (biomass) grinding process;
- studying biomass grinding equipment construction, especially on hammer mills;
- theoretical study of the working process realized by the hammer mill organs;
- modelling and finite element simulation of stresses from the hammer mill working hammer joints;
- determining the hammer rotor speed on energetic plant (Miscanthus and willow) grinding degree, respectively on the energetic consumption;
- determining the influence of sieve size on energetic plant grinding and on specific energetic consumption;
- establishing correlations between hammer mill grinding process parameters.

5.2. Describing utilized equipment during experiments

In order to pass through each proposed stage, different equipment were used, out of which the most important one was the hammer mill MC-22 for vegetal waste, which is a part of the agri-pellet fabrication flow, and with which the energetic plant grinding was achieved.

Hammer mill MC-22, with articulated hammers, has a rotor length of 500 mm, hammer distribution diameter of ϕ220 mm, and grinding chanber diameter of ϕ500 mm, also the electric motor power is 2kW, electric motor speed is 3000 rpm, grinding capacity is 900 m^3/h. The sieve used during experiments was interchangeable, with orifice sizes of 25, 16, 10 and 7 mm for Miscanthus biomass, and 16, 10 and 7 mm for willow biomass.

Other equipment used during testing were a chronometer, a roulette, a digital caliber, an analytic balance model AV 220, a lab dryer UFE 500, a revmeter and the digital photo camera,

Fig. 5.1 – Hammer mill MC-22

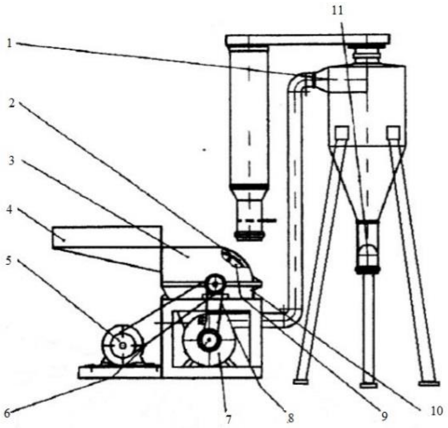

Fig. 5.2. Hammer mill MC-22 constructive schema [10])

5.3. Experimental determination methodology

Fig. 5.12. Experiment course schema for analyzing hammer mills working process

For experiment tests, 10 probes of 0,5 kg from different areas were taken, both for Miscanthus and energetic willow. Material particle dimensions were measured in grinded state and the average particle dimension was determined.

So, Miscanthus particles had average size of 123-127 mm, whilst energetic willow particles had sizes between 25 – 47 mm (over 85% of the material). Before executing the first test, a few preliminary trials were realized, which contributed to choosing hammer mill adjustment parameters. Experimental tests were realized using different quantities of material, in the case of Miscanthus 5 kg of material were used on most tests, and in the case of energetic willow 4 or 3 kg were used. All data were centralized, and then processed with the help of Excel, Origin 7.0, Table Curve2D, Statica software programs.

5.4. Experimental results

Table 5.3. Experiemental parameters resulted from experimental researches for grinding Miscanthus X Giganteus biomass

Hammer type	**Sieve orifice size**	**Rotor speed**	**Material humidity**	**Grinding consumed energy**	**Grinded particle average size**	**Grinding degree appreciation index**
	ϕ_s	**n**	**u**	**E_s**	**dm**	**λ**
	(mm)	(rot/min)	(%)	(kJ/kg)	(mm)	
Type A hammer– with one corner edge	16	3000	11,19	42,93	18,04	6,93
		2850	11,05	40,81	16,65	7,51
		2700	11,07	48,44	16,80	7,44
		2550	11,13	42,96	17,24	7,25
		2400	11,09	55,32	17,28	7,24
Type B corner– with two corner edges	16	3000	10,34	114,28	15,48	8,08
		2850	10,20	102,14	14,85	8,42
		2700	10,29	76,84	15,87	7,88
		2550	10,23	80,86	15,62	8,00
		2400	11,06	48,45	16,68	7,49

Tables 5.3, 5.4 present experimental data only for the ϕ16 mm orifice size sieve, both for Miscanthus, as well as willow. Results for sieves of ϕ25 mm and ϕ10 mm, for Miscanthus, respectively ϕ10 mm and ϕ7 mm for willow are in annexes 5.1 – 5.4. Also, according to grinding theory, which makes refference to the distribution of material particles after their size, changing these sizes can include particles from the smallest to the largest.

Table 5.4. Experiemental parameters resulted from experimental researches for grinding Salix viminalis (willow) biomass

Hammer type	**Sieve orifice size**	**Rotor speed**	**Material humidity**	**Grinding consumed energy**	**Grinded particle average size**	**Grinding degree appreciation index**
	ϕ_s	**N**	**u**	**E_s**	**dm**	**λ**
	(mm)	(rot/min)	(%)	(kJ/kg)	(mm)	
Type A hammer– with one corner edge	16	3000	10,12	30,49	10,40	12,02
		2850	9,09	28,36	9,40	13,30
		2700	8,89	26,83	10,76	11,61
		2550	8,87	40,85	10,56	11,84
		2400	8,90	32,72	10,80	11,57
Type B corner– with two corner edges	16	3000	10,23	44,03	9,51	13,15
		2850	10,76	33,11	9,75	12,82
		2700	10,17	29,61	9,82	12,73
		2550	10,81	25,59	11,62	10,76
		2400	10,20	28,70	11,16	11,21

Table 5.5. Percentage of particles on dimension classes for the ϕ16 mm sieve

Hammer type	**Material type**	**Dimension classes**	**Rotor speed, n (rpm)**				
			3000	**2850**	**2700**	**2550**	**2400**
Type A hammer– with one corner edge	Miscanthus	0	0	0	0	0	0
		5	7,745	12,93	11,135	13,71	14,2275
		10	25,3675	31,85	29,21	25,96	25,775
		16	41,6025	48,8375	46,305	42,7275	44,705
		21	99,2625	99,6275	98,07	97,915	99,075
Type B corner– with two corner edges	Miscanthus	0	0	0	0	0	0
		5	12,495	18,36	14,2925	14,2575	13,545
		10	32,45	35,2625	30,2725	29,37	27,5725
		16	54,025	55,8025	51,2225	53,6625	46,23
		21	97,485	97,6325	97,5725	97,5475	97,705
Type A hammer– with one corner edge	Willow	0	0	0	0	0	0
		5	14,99	23,693	9,982	12,357	12,812
		10	45,753	58,349	43,315	44,689	40,624
		16	92,657	91,765	92,459	92,488	92,144
		21	99,1505	99,207	98,958	98,926	98,937
Type B corner– with two corner edges	Willow	0	0	0	0	0	0
		5	29,888	29,88	22,38	13,989	13,791
		10	64,635	64,415	60,71	50,403	48,883
		16	85,529	83,624	87,689	80,807	85,749
		21	99,282	99,296	99,199	99,135	99,294

During this paper the granulometric analysis using the material distribution law type Rosin-Rammler was used. For a certain set of data, presented in table 5.5 from the total of experimental results, the cumulative Rosin Rammler distribution law was applied.

5.5. Verifying some popular theories regarding basic grinding with experimental results

During this sub-chapter, on the basis of Kick, Bond and Rittinger established relations, which describe grinding energy consumption, coefficients of these relations were determined having real values into consideration (experimentally determined) for biomass grinding energy. In order to apply energy equations, the particle average diameter was determined before grinding both for Miscanthus, as well as for willow, their values being measured at 125 mm, respectively betwee 25 – 47 mm.

5.5.1. Verifying committed theories regarding consumed energy in relation to experiment conditions

Utilizing Kick, Bond and Rittinger and using Microsoft Office Excel, values of these relations coefficients C_k, C_R, C_B were calculated (presented in tables 5.6, 5.7, 5.8).

Table 5.7. Values of C_k, C_R, C_B constants for ϕ16 mm Miscanthus sieve

Hammer tyoe	Rotor speed	Dimensions of material particles before grinding	Dimension of grinded material particles	Grinding degree	Consumed energy	Kick constant $E = C_k \ln\frac{D}{d}$	Rittinger constant $E = C_R\left(\frac{1}{d}-\frac{1}{D}\right)$	Bond constant $E = C_B\left(\frac{1}{d^{0.5}}-\frac{1}{D^{0.5}}\right)$
	rpm	mm	mm		kJ/kg	kJ/kg	kJ m kg^{-1}	kJ m^{0,5} kg^{-1}
A	3000	125	18,04	6,929	42,934	22,180	0,905	9,299
	2850	125	16,65	7,508	40,811	20,243	0,784	8,291
	2700	125	16,80	7,442	48,437	24,133	0,940	9,910
	2550	125	17,24	7,251	42,956	21,682	0,859	8,971
	2400	125	17,28	7,236	55,320	27,953	1,109	11,572
B	3000	125	15,48	8,076	114,282	54,711	2,019	21,936
	2850	125	14,85	8,415	102,136	47,951	1,722	18,995
	2700	125	15,87	7,878	76,845	37,230	1,397	15,036
	2550	125	15,62	8,003	80,857	38,877	1,443	15,629
	2400	125	16,68	7,492	48,449	24,058	0,933	9,860

Following and analyzing data from the table we could see that values of C_k were between 29.66 – 47.11 kJ/kg limits for type A hammer ϕ25 mm sieve, respectively between 17.58 – 35.31 kJ/kg for type C hammer and the same sieve used, for Miscanthus biomass, which means that the specific grinding energy is significantly smaller for the two corner edges hammer compared to the one corner edge hammer.

Reffering to constant C_R , from Rittinger relation, it varies betwenn limits of 0.82 – 2.69 kJ·m/kg, in relation to the hammer type and rotor speed, for ϕ25 mm sieve, respectively 0.71 – 2.02 kJ·m/kg, for ϕ16 mm sieve, and between 0.45 – 1.34 kJ·m/kg for ϕ10 mm sieve, in the case of Miscanthus.

In the hammer type, for example, for type C hammer, coefficient C_R is modified with rotor speed and mill sieve diameter, from0.76 kJ·m/kg for ϕ10 mm sieve and 1.02 kJ·m/kg for ϕ25 mm sieve at 2550 rpm speed.

Analyzing the data from the tables we can observe that C_B gets modified from 9.54 kJ·$m^{0,5}$/kg to 24.67 kJ·$m^{0,5}$/kg for ϕ25 mm sieve, in relation with hammer type and rotor speed, respectively between 8.24 – 21.93 kJ·$m^{0,5}$/kg ϕ16 mm sieve and between 6.1 – 16.7 kJ·$m^{0,5}$/kg for ϕ10 mm sieve. For a constant speed, for example 2400 rpm, values of C_B, are between 9.63 – 20 kJ·$m^{0,5}$/kg for 25 mm sieve in relation with hammer type, respectively between 9.86 – 14.87 kJ·$m^{0,5}$/kg for 16 mm sieve and between 8.47 – 14.07 kJ·$m^{0,5}$/kg for the 10 mm sieve.

Values of constants C_k, C_R, C_B determined for Miscanthus biomass using MC-22 mill (used in experiments in this thesis) can be compared t o values obtained by other researchers, but the speciality literature doesn't show data linked to this plant and neither for the case of hammer mills used for biomass grinding.

Table 5.9. Values of constants C_k, C_R, C_B for ϕ16 mm sieve, used on willow

Hammer type	**Rotor speed**	**Sieve orifice size**	**Grinding degree**	**Consumed energy**	**Kick's constant**	**Rittinger's constant**	**Bond's constant**
	rot/min	mm		kJ/kg	kJ/kg	kJ m kg^{-1}	kJ $m^{0,5}$ kg^{-1}
A	3000	10,40	12,016	30,495	12,265	0,346	4,371
	2850	9,40	13,303	28,359	10,958	0,288	3,787
	2700	10,76	11,614	26,831	10,942	0,316	3,940
	2550	10,56	11,840	40,854	16,530	0,471	5,917
	2400	10,80	11,572	32,717	13,362	0,387	4,816
B	3000	9,51	13,147	44,032	17,092	0,453	5,928
	2850	9,75	12,817	33,110	12,980	0,350	4,537
	2700	9,82	12,730	29,606	11,638	0,315	4,076
	2550	11,62	10,762	25,590	10,770	0,328	3,967
	2400	11,16	11,205	28,700	11,877	0,352	4,323

Values of Kick coefficient is between 7.02 – 19.0 kJ/kg limits for all sieves, all hammer types and all speed levels. We can observe that the smallest value of Kick coefficient is found for type C hammer and rotor speed of 2400 rpm. Reffering to Rittinger coefficient, we can say that $C_{R,}$ varies between 0.15 – 0.49 kJ·m/kg for all types of hammers, sieves and rotor speeds. If the rotor speed is 2850 rpm, then for type A hammer Rittinger coefficient has values of between 0.29 – 0.35 kJ·m/kg, according to the type of sieve used, the largest value being for the ϕ7 mm sieve.

We could observe a maximum of C_B coefficient of 6.52 kJ·$m^{0,5}$/kg for type A hammer and speed of 2400 rot/min and a minimum of 2.57 kJ·$m^{0,5}$/kg for type C hammer and spped of 2400 rpm. If we analyze values of C_B for each sieve in particular, we have new values in the range of 2.57 kJ·$m^{0,5}$/kg for type C hammer and 5.92 kJ·$m^{0,5}$/kg for type B hammer, both for ϕ16 mm sieve,

$3.07\ \text{kJ}\cdot\text{m}^{0,5}/\text{kg}$ for type C hammer and $6.52\ \text{kJ}\cdot\text{m}^{0,5}/\text{kg}$ for type A hammer, both for ϕ10 mm sieve, and $2.45\ \text{kJ}\cdot\text{m}^{0,5}/\text{kg}$ for type A hammer and $5.54\ \text{kJm}^{0,5}/\text{kg}$ pentru ciocanul de tip both for ϕ7 mm sieve.

Similar to our research for Miscanthus and willow, the speciality literature doesn't show links between these plants and hammer mills.

5.5.2. Grinded material distribution determination on dimension classes and correlation with Rosin – Rammler law

For experimental data correlation regarding granulomentric analysis of the grinded material, regression analysis was applied with Rosin Rammler law. Known relation for cumulative distribution of the screened material on sieves T(x) was used, (relation 5.1). Both for Miscanthus and willow, experimental values obtained from granulometric analysis on ϕ16 mm sieve and type A hammers (one corner edge) and type B hammers (two corner edges), were chosen. Regression analysis was realized using Matlab calculus software.

Table 5.12. Experimental coefficient values of regression analysis

Biomass type	**Hammer type**	**Rotor speed (rpm)**	**Experimental coefficients**		
			b	**n**	**R^2**
Miscanthus X Giganteus	**A**	3000	-772	-2,659	0,853
		2850	-384	-2,471	0,8607
		2700	-450,1	-2,498	0,8642
		2550	-655,4	-2,596	0,8345
		2400	-779	-2,681	0,8417
Salix vinimalix	**B**	3000	-24,28	-1,831	0,9854
		2850	-22,58	-1,787	0,9842
		2700	-42,24	-2,025	0,9844
		2550	-72,23	-2,109	0,9756
		2400	-102,5	-2,264	0,9717

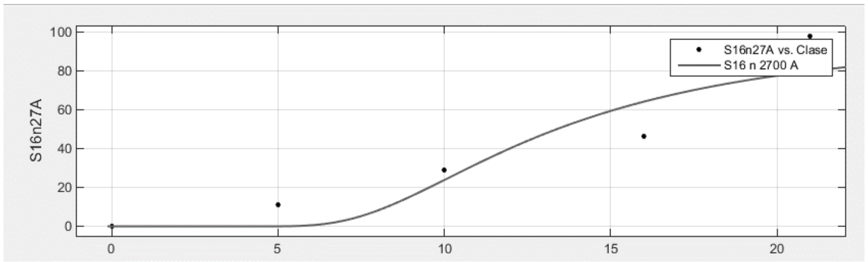

Fig. 5.14. Miscanthys granulometric distribution T(x), type A hammer and ϕ16 mm sieve

5.6. Researches regarding mill constructive parameter influence on grinding energy consumption

5.6.1. Sieve orifice diameter influence on specific energy consumption

According to resulted graphs, we can observe that using type A hammer leads to smaller energetic consumption compared to the other hammer types, but both speed and sieve must be choese accordingly.

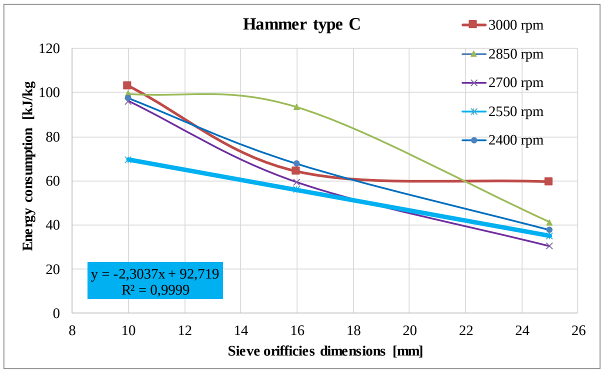

Fig. 5.17. Specific consumed energy variation in relation to sieve orifices for type C hammer and Miscanthus biomass

Analyzing the graphs from figures 5.19 – 5.22 we can see the general tendency of lowering energy consumption when using higher orifices for the sieves, even if there are speeds on which the variation tendency is changing.

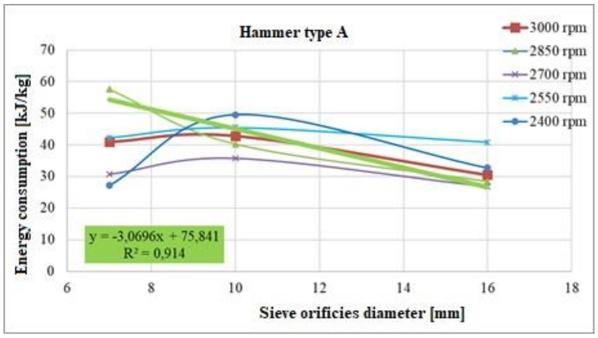

Fig. 5.19. Specific consumed energy variation in relation to sieve orifice diameter for type A hammer, using energetic willow biomass

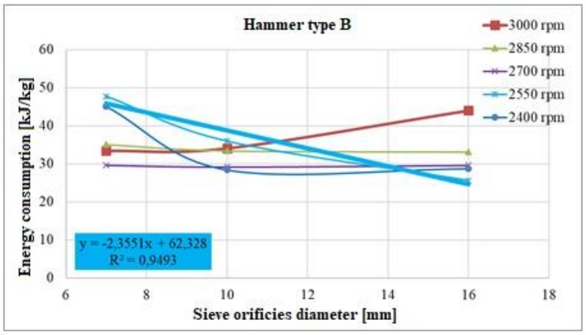

Fig. 5.20 Specific consumed energy variation in relation to sieve orifice diameter for type B hammer

Experimental results mainly recommend using type A hammer and type C hammer, to which the most values of rotor speed present decreasing variations for specific energy consumption with a rise of sieve orifices.

5.6.2. Hammer type influence on grinding consumed energy

According to graphs for both Miscanthus and energetic willow, we can observe that using a certain type of hammer leads to smaller energy consumption than on other types of hammers, with the condition that the sieve and speed must be chosen accordingly. For example, from the energy consumption variation analysis for ϕ7 mm sieve, in the case of energetic willow, we can't indicate using acertain type of hammer at a specific speed for an optimum energy consumption because the energy consumption variation presents values between large limits no matter the values of the two parameters.

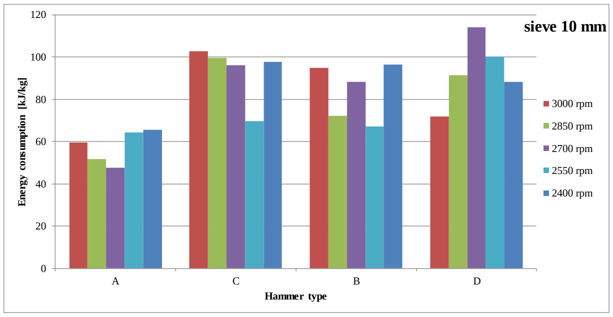

Fig. 5.25. Specific consumed energy variation in relation to the hammer type for 10 mm sieve, on Miscanthus biomass

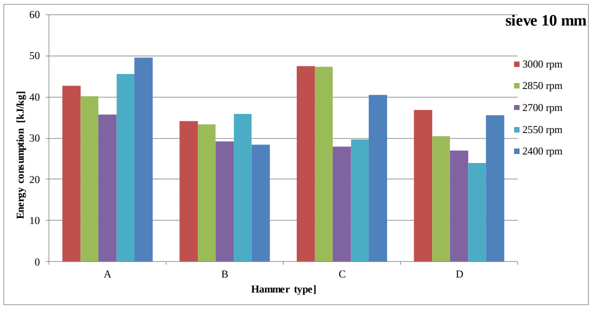

Fig. 5.27. Specific consumed energy variation in relation to the hammer type for 10 mm sieve, on energetic willow biomass

5.7. Researches regarding mill constructive parameters influence on grinded material quality

Experimental data shown in tables 5.3, 5.4 and annexes 5.1 – 5.4 were used for drawing the grinded particle average dimension variation curves, for both types of biomass. Graphs that represent this variation are presented in figures 5.29 – 5.36.

5.7.1. Sieve orifice diameter influence on grinded particles average dimensions

As espected, the grinded particle dimension variation general tendency is an ascending one, with using larger orifice sizes for the sieves, for all speeds and hammer types used during experiments.

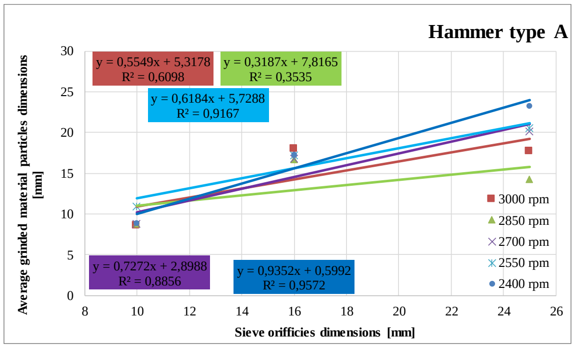

Fig. 5.29. Grinded material particle average dimension variation in relation to the sieve's orifice diameter for type A hammer and Miscanthus biomass

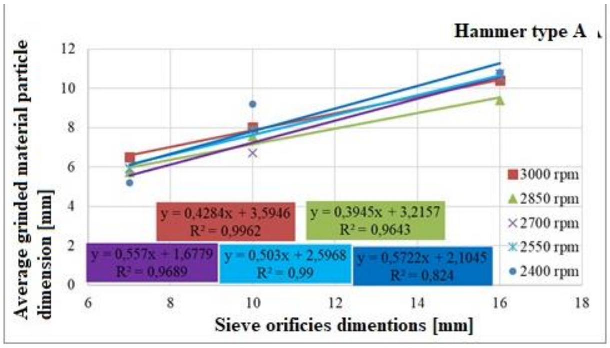

Fig. 5.33. Grinded material particle average dimension variation in relation to the sieve's orifice diameter for type A hammer amd willow

Value set distribution order for each sieve used is random, even if the lines are relatively close. It is difficult to say, though, what are the real grinded particle dimensions in the case where more particles have a much larger size compared to the other two dimensions and the sieve orifice size.

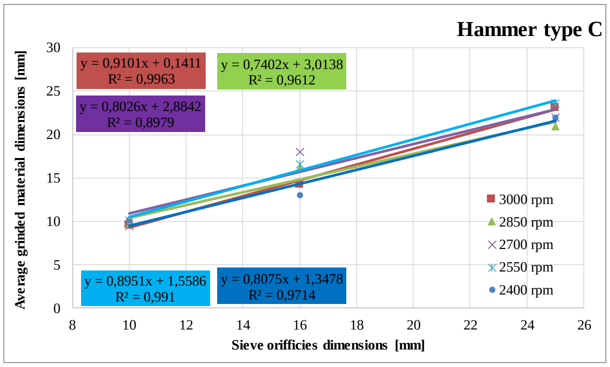

Fig. 5.31. Grinded material particle average dimension variation in relation to the sieve's orifice diameter for type C hammer and Miscanthus biomass

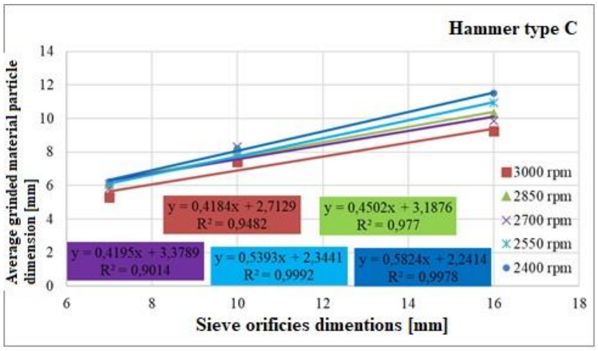

Fig. 5.35 Grinded material particle average dimension variation in relation to the sieve's orifice diameter for type C hammer and Miscanthus biomass

When it comes to grinded material average size variation, when grinding willow, with sieve orifice diameter, we can observe a linear variation for all types of hammers and all experimental rotor speeds.

5.7.2. Hammer type influence on grinded particles average dimensions

Reffering to hammer type influence, for Miscanthus biomass, on grinded particle average size, for ϕ25 mm sieve we can observe a variation of values within large limits for type A hammer (14 -23 mm) and for type B hammer (16 – 21 mm) comparing them to type C and D hammers, for which particle sizes are between 21 – 24 mm, respectively 22.5 – 24.5 mm.

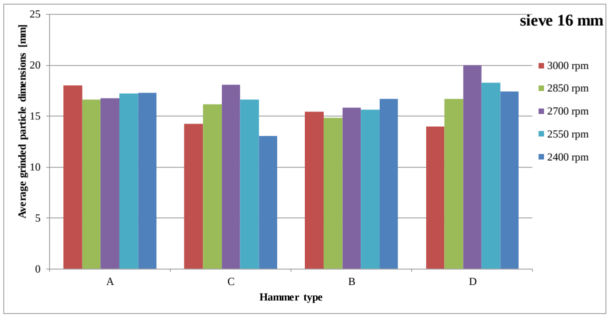

Fig. 5.38. Grinded material particle average dimension variation in relation to hammer type for 16 mm sieve, Miscanthus biomass

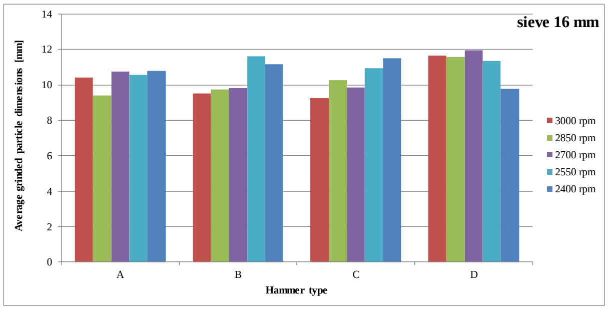

Fig. 5.40. Grinded material particle average dimension variation in relation to hammer type for 16 mm sieve, energetic willow

If we analyze the situation from the rotor speed point of view we can say that grinded material size for 2850 rot/min rises with changing the hammer type used for energetic willow biomass (from type A hammer to type D hammer). Grinded biomass particles average size is roughly 9 mm.

5.8. Researches regarding the influence of biomass physical properties on specific energy consumption and on grinded material quality

5.8.1. Influence of material moisture on grinding energy consumption

Reffering to the material humidity influence on specific energy consumption we can observe that the same variation of parameters is not the same for all cases, so that a unitary conclusion can’t be drawn. We can conclude that humidity must not be too small or too large in percentage, because the lignin from biomass composition can lead to higher energetic consumption, when humidity levels are too low.

5.8.2. Influence of material moisture on average dimensions of grinded particles

We can observe that particles of large sizes are obtained through higher humidity levels and smaller sizes for smaller humidity levels. For a proper grinding, with small material particle sizes and low values of consmed energy, it is necessary that biomass humidity to be lower. Our recommendation is that humidity should be below 10%, or even smaller in order for Miscanthus stalks to be finely grinded (divided).

If we analyze experimental point dispersion for energetic willow we can observe that the most values for grinded particle average size were recorded for humidity levels of 10 – 10.5%. Material particle values for this situation were between 5.19 – 6 mm, under the sieve’s orifice size (but very close to it).

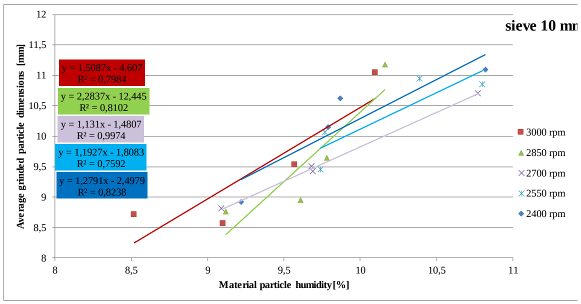

Fig. 5.51. Grinded material particle average dimension variation in relation to hammer type for 10 mm sieve, Miscanthus biomass

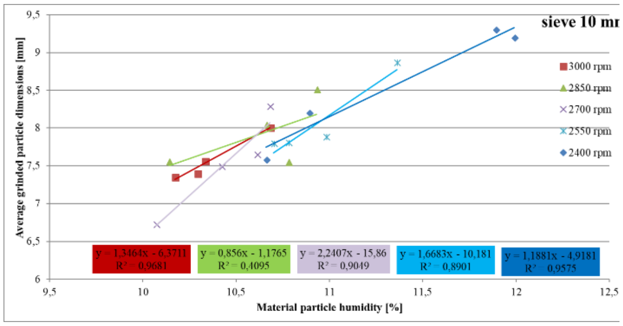

Fig. 5.53. Grinded material particle average dimension variation in relation to hammer type for 16 mm sieve, energetic willow

5.9. Researches regarding mill functional parameters influence on grinding indexes

5.9.1. Influence of hammer mill rotor speed on grinding consumed energy

Specific consumed energy variation was analyzed also according to rotor speed for each type of hammer.

Type B hammer (Miscanthus) presents ununiform specific grinding energy curves according to speed, observing that there are speed values that can’t be utilized for process optimization because they don’t fit into mathematical rules. Disregarding some speed values, the process could be optimized in certain limits, according to the sieve used and the destination of the material if its physical properties remain unchanged.

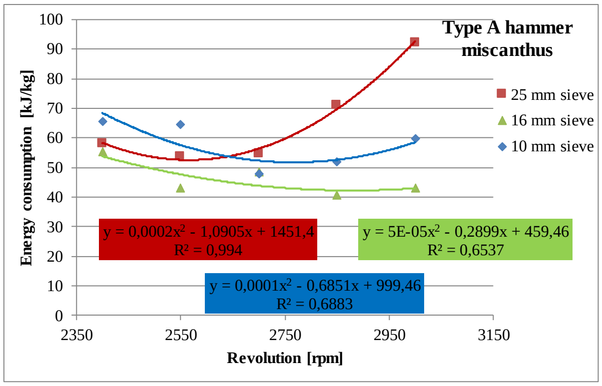

Fig. 5.55. Grinding process consumed energy variation in relation to rotor speed for type A hammer, for grinding Miscanthus biomass

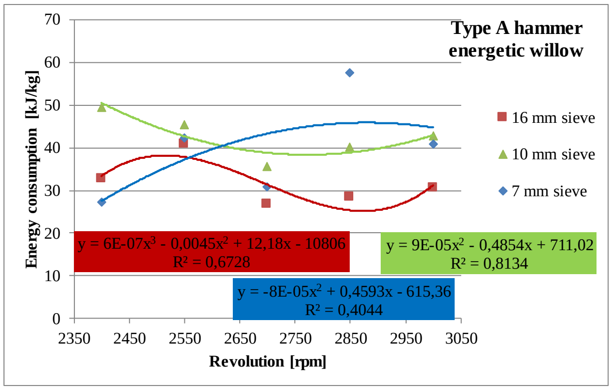

Fig. 5.59. Grinding process consumed energy variation in relation to rotor speed for type A hammer

Grinding process optimization (energetic willow) for type D hammer from the energy consumption point of view, is possible if we use the 10 mm sieve, which presents a minimum energy consumption at rotor speed of 2600 rot/min.

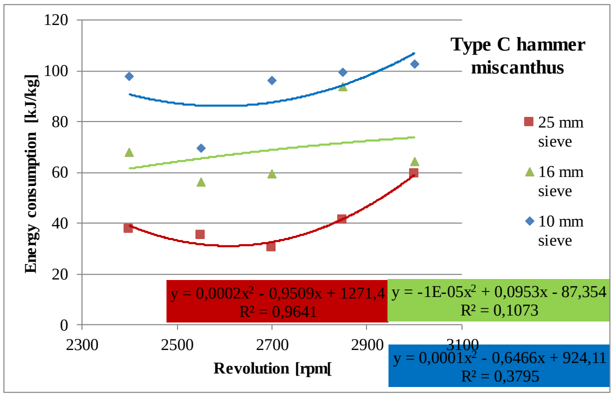

Fig. 5.57. Grinding process consumed energy variation in relation to rotor speed for type C hammer, for grinding Miscanthus biomass

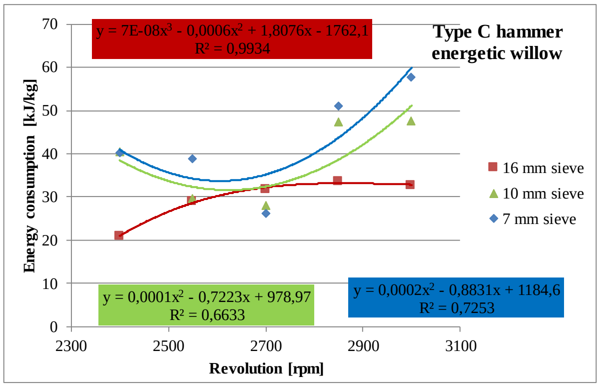

Fig. 5.61. Grinding process consumed energy variation in relation to rotor speed for type C hammer

5.9.2. Influence of hammer mill rotor speed on average dimensions of grinded particles

Careful observations on grinded particles average size variation shows that there is a descending tendency with a rise of rotor speed, no matter what sieve is used, if we disrecard certain speed values considered unusable (probably random errors).

We considere that an important influence on grinded particle size is that of the intake air flow, most particles with sizes close to the size of the sieve's orifices (or even greater) pass relatively easy through orifices, especially when using low working flows (Miscanthus).

The general observation (energetic willow) is that with higher rotor speed comes lower grinded particle sizes, but these are very close to sieve's orifice size, which indicates the importance of air flow for for eliminating under the sieve the particles that have passed through the orifices.

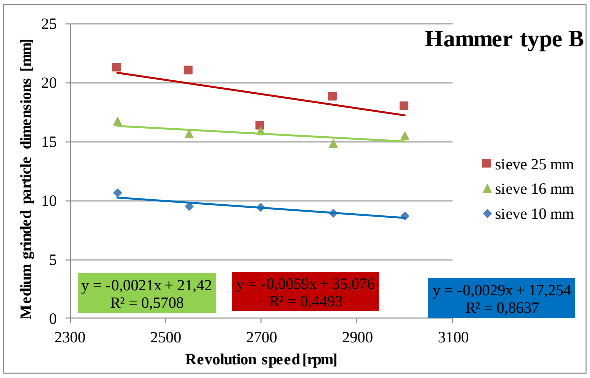

Fig. 5.64. Grinding process consumed energy variation in relation to rotorspeed for type B hammer, for grinding Miscanthus biomass

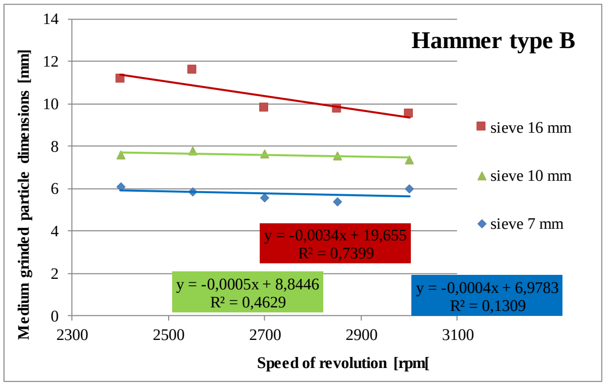

Fig. 5.68. Grinding process consumed energy variation in relation to rotor speed for type C hammer, for grinding energetic willow

5.10. Conclusions regarding experimental researches

Reffering to the analysis regarding physical properties influence on specific energy consumptiom and on grinded material quality we can mention that for the influence of humidity on the grinded particle average size, we observed that particles of large sizes are produced for higher humidity levels and smaller ones are produced with smaller humidity levels. Also, inside this chapter, established theories of consumed energy in relation with experimental contitions were verified, determining Kick, Bond and Rittinger coefficients. When it comes to modifying C_k coefficient with sieve orifice diameter at hammer mill rotor, it varies in relation with the type of hammer used and rotor speed. So, for type A hammer, at speed of 2550 rot/min, C_k coefficient has values of between 21.68 kJ/kg for ϕ16 mm sieve and 29.66 kJ/kg for ϕ25 mm sieve. Values of constants C_k, C_R, C_B determined for Miscanthus biomass with the MC-22 hammer mill (used during experiments) can be compared to values obtained by other researchers, but the speciality literature doesn't present data linked to this plant or in the case of hammer mills used for grinding biomass. If we appreciate C_B from certain speeds point of view, for example 3000 rot/min, then values are between 3.45 – 5.92 kJm^{0,5}/kg for ϕ16 mm sieve, 3.86 – 5.4 kJ·m^{0,5}/kg for ϕ10 mm sieve and 3.31 – 5.29 kJ·m^{0,5}/kg for ϕ7 mm sieve(energetic willow).

Chapter 6.- Contributions regarding biomass grinding process optimization using hammer mills

6.1. General notions regarding process optimization

In this chapter, going through all stages mentioned above for vegetal material grinding hammer mill working processes was practiced. Taking into consideration the intensly arbitrary character of many of the parameters which characterize hammer mill working process, a careful classification of the research objectives is necessary and also the estimation precision target. Because the way of approaching the problem is relatively new in the domain of grinding processes (not only for hammer mill, but in general for different types of mills), and also relatively general to be applied in many areas of engineering activity, estimating obtained results should be realized through other papers conclusions to this type of working processes modelling (enhancing and eventually, optimizing). Highly interesting for the present thesis, is article [26] signed by an Iranian research team. The authors [26] study specific consumed energy variation in hammer mills in relation to the diameter of sieve orifices and to the grinded vegetal material (alfalfa). Their first conclusion is that the specific energy consumption rises with a lowering on sieve orifice diameter used in experiments.

The qualitative conclusion was found also in the present paper. Using just linear regression, authors [26] obtained a regression coefficient with the value of 0.68–0.7. Using polynomial non-linear regressions, regression coefficients were over 0.7, leading all the way to 0.9.

6.2. Describing hammer mill working process, as a system

Grinding phenomenon for Miscanthus and willow stalks using hammer mills with four types of hammers, was studied, after an experimental plan which containes a number of 12 parameters. The list of parameters considered in the experimental plan, and consequently, in the theoretical model, is present in table 6.1.

Table 6.1 List of parameters that defin hammer mills grinding process

Nr.	**Numele parametrului**	**Notation**	**u.m.**
1	Sieve diameter	d_s	m
2	Rotor speed (rotation frequency)	v	s^{-1}
3	Batch processing time	t	s
4	Batch mass	m	kg
5	Grinded material flow	q	kg/s
6	Tension of actionning electric current	U	V
7	Intensity of actionning electric current	I	A
8	Power of actionning electric current	P	W
9	Energy on a batch	E	J
10	Consumed energy on the unit of processed mass	ε	J/kg
11	Humidity	u	%
12	Grinded material granulation distribution	g_r	%

A number of 6 parameters (orange coated spaces on table 1) was measured and other four parameters were calculated (green coated spaces in table 6.1), using relations:

$$q = \frac{m}{t} \tag{6.1}$$

$$P = 0.9\sqrt{3}UI \tag{6.2}$$

$$E = P \cdot t \tag{6.3}$$

$$\varepsilon = \frac{E}{m} \tag{6.4}$$

Out of the hammer mill working process parameters, there is a high number with arbitrary behavior.

6.3. Grinding process statistical modelling using hammer mills

Correlations between parameters that describe hammer mill process. From the 12 parameters that appear in table 6.1, and that define the process, (q, m, t, P, U, I, E, ε) are linked through the four relations (1)-(4). Only four of these parameters (d_s, v, u, g_r) are free.

According to experiments, here is the next parameter classification (fig. 6.2):

- input parameters - material: m, t, q, u;
- feeding parameters – energy: P, U, I, E, ε;
- command and adjustment parameters: d_s, v;
- output parameters - quality: g_r.

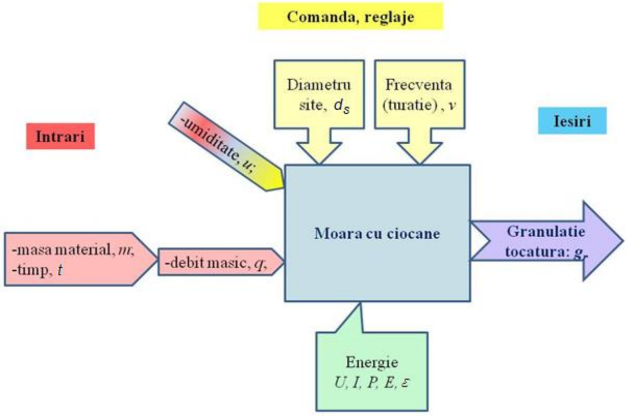

Fig. 6.2 System schema for the hammer mill

For describing some internal system relations, as well as for describing relations between output, input and control sizes, there are no applicable physical relations. This situation is given by the profoundly arbitrary character of the described working process.

Only the static energy dependency parameters were estimated from the process command parameters (feeding flow, sieve orifice size, speed as adjustment parameters). The correlation between consumed energy in the process and each of the three parameters, the identifying index (square of correlation), and the linear regression bent, were realized using Excel MS Office, with the relations:

$$corr(x,y) = \frac{\sum_i (x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2\,(y_i - \bar{y})^2}} \tag{6.5}$$

$$\mathrm{R}^2 = \frac{\sum_i (y - \bar{y})^2 - \sum_i (y - \hat{y})^2}{\sum_i (y - \bar{y})^2} \tag{6.6}$$

$$b = \frac{\sum_i (x_i - \bar{x})\,(y_i - \bar{y})}{\sum_i (x_i - \bar{x})^2} \tag{6.7}$$

The analysis of data presented in table 6.2 shows a correlation between energy and sieve orifice size, without a negative exception, which proves that there is a relation between these parameters, of almost reverse proportionality. Regarding both cases (Miscanthus and energetic willow grind), in the seven out of eight cases, the correlation shows a reverse dependency between consumed energy and the used sieve orifice diameter of approximately 87.5%

Table 6.2 Static characteristics regarding correlation between energy and parameters of command and adjustment, when grinding Miscanthus giganteus biomass

Parameter pair	**Correlation (rel.5)**	**Determination coefficient R^2 (rel.6)**	**Linear regression bent (rel.7)**	**Covariance P (rel.8)**	**Kurtosis (rel.9)**
Hammer with one edge corners					
Energy – Sieve orifice size	-0.349	0.122	-1.164	-54.999	-0.603
Energy – Rotor speed	0.232	0.054	1.504	18.798	4.122
Energy – Feeding flow	-0.329	0.109	-199.03	-0.286	0.177
Hammer with three edge corners					
Energy – Sieve orifice size	-0.847	0.717	-2.950	-139.382	-1.270
Energy – Rotor speed	0.285	0.081	1.934	24.161	-0.618
Energy – Feeding flow	-0.845	0.713	-266.34	-1.536	-1.485
Hammer with two edge corners					
Energy – Sieve orifice size	-0.627	0.393	-2.969	-140.279	-0.571
Energy – Rotor speed	0.153	0.024	1.691	21.134	0.591
Energy – Feeding flow	-0.635	0.404	-398.64	-0.659	-0.900
Hammer with oblique corners					
Energy – Sieve orifice size	-0.629	0.396	-2.602	-122.937	-0.516
Energy – Rotor speed	-0.305	0.093	-2.454	-30.6795	1.445
Energy – Feeding flow	-0.838	0.702	-385.43	-1.4706	-0.958

For the dependency between energy and hammer rotor frequency, in the case in which the material is willow, correlation is always positive (thus it suggests a direct dependency), but insignificant for the case of hammers with two edge corners, moderate for hammers with three corner edges and weak for oblique edge hammers.

Table 6.3 Static characteristics regarding correlation between energy and parameters of command and adjustment, when grinding Miscanthus giganteus biomass

Parameter pair	**Correlation (rel.6.5)**	**Determination coefficient R^2 (rel.6.6)**	**Linear regression bent (rel.6.7)**	**Covariance P (rel.6.8)**	**Kurtosis (rel.6.9)**
Hammer with one edge corners					
Energy – Sieve orifice size	-0.439	0.193	-1.013	-14.180	-1.098
Energy – Rotor speed	0.039	0.002	0.095	1.192	-0.137
Energy – Feeding flow	-0.690	0.476	-88.970	-0.39831	-1.605
Hammer with three edge corners					
Energy – Sieve orifice size	-0.334	0.111843	-1.476	-20.658	-0.793
Energy – Rotor speed	0.084	0.007	1.433	17.914	-0.240
Energy – Feeding flow	-0.238	0.057	-83.025	-0.280	-1.407
Hammer with two edge corners					
Energy – Sieve orifice size	-0.550	0.303	-0.570	-7.973	-1.192
Energy – Rotor speed	0.505	0.255	0.151	1.882	-1.274
Energy – Feeding flow	-0.481	0.231	-16.645	-0.139	-1.7345
Hammer with oblique corners					
Energy – Sieve orifice size	0.396	0.157	0.930	12.814	-0.323
Energy – Rotor speed	0.268	0.072	0.723	8.295	0.001
Energy – Feeding flow	-0.468	0.219	-68.113	-0.235	-1.335

6.4 Considerations regarding hammer mills working process optimization

As optimization parametes, meaning arguments for objective functions, it is mandatory to consider process command or adjustment parameters, like frequency v (respectively rotor speed), sieve orifice size, d_s.

Rotor frequency is the command that gives speed to the system. Tension U and intensity, I of the feeding current is measured. Using measured values for tension and intensity, we calculate the power and energy, respectively the energy on processed mass unit ε. Sieve orifice diameter d_s is chosen, mainly for calibrating maximum length of grinded material.

Objective functions taken into consideration in this stage of modelling (in which objective functions like endurance, reliability, etc. have been excepted) are of three types: energetic, economical. and production quality.

Objective functions of energetic type that can be considered are:

- energy E calculated from parameters U and I and having as arguments parameters v, d_s, u, eventually m and t, or synthetically q;
- energy ε calculated from parameters U and I and having as arguments parameters v, t, u, eventually m and t, or synthetically q;
- specific energy for working capacity, w

6.4.1. Objective function describing hammer mills working process quality, used for grinding vegetal material

Experiments realized for vegetal material grinding with the help of mills equipped with different hammer types, consequently realized the resulted material sorting.

Forming a direct function on existing normalized data was tried, thus through probability density interpolation. A second degree polynomial interpolation was tried in four variables $P = P(x, d_s, v, q)$, where x is the maximum size for chopped segments.

$$\begin{aligned} P(x, d_s, \nu, q) = {} & P_0 + a_1x + a_2x^2 + b_1d_s + b_2{d_s}^2 + c_1\nu + c_2\nu^2 + d_1q + d_2q^2 \\ & + a_3xd_s + a_4x\nu + a_5xq + b_3d_s\nu + b_4d_sq + c_3\nu q \end{aligned} \tag{6.14}$$

The function that approximates through interpolation (usin the smallest squares method) probability that the grinded particles have inferior maximum sizes to a given size, has the form of:

$$\begin{aligned} P(x, d_s, \nu, q) = {} & 545.009 + 3945.389x - 0.642x^2 - 852.676d_s \\ & - 244158.187{d_s}^2 - 28.399\nu + 0.24\nu^2 + 949.638q - 7802.92q^2 \\ & + 155488.247xd_s - 143.957x\nu + 17010.48xq + 181.595d_s\nu \\ & - 0.165d_sq + 34.85\nu q \end{aligned} \tag{6.14'}$$

Realizing the math, we can see there are also losses (fig. 6.5), which in turn can form the subject for an objective function that must be minimized.

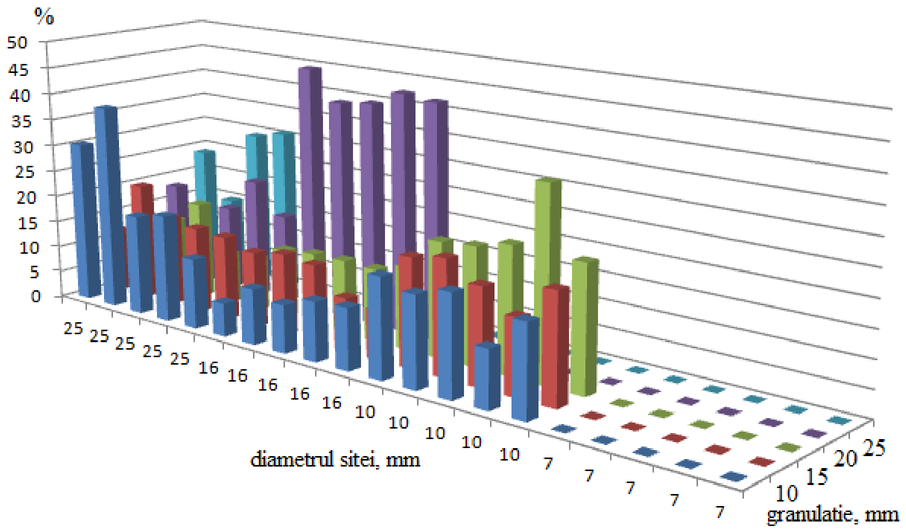

Fig. 6.3. Graphical representation regarding product granulation

Analyzing data from table 6.4, we can see that, regarding process influence, as an absolute size, polynomial coefficients indicate an intense dependency of function (6) to the: d_s^2, d_s, xd_s, q terms. As a measurement order, distribution of coefficients is similar for the four hammer types. Signals differ for some coefficients, but not for the dominant ones. Coherency in the case of chopping Miscanthus stalks is evident, when it comes to the polynomial structure of interpolation.

Table 6.4 Coefficients and estimation solution quality performance (6.14) for the four hammer types used for grinding Miscanthus stalks

	One corner edges hammer	Two corner edges hammer	Three corner edges hammer	Oblique edges hammer
P_o	545.009	7.647	128.178	-191.809
a_1	3945.389	1840.053	-773.96	4381.88
b_1	-852.676	11921.83	8528.7	13948.771
c_1	-28.399	-1.153	-8.827	5.781
d_1	949.638	-998.537	250.614	-1068.779
a_3	155488.247	135065.701	260449.374	137745.435
a_4	-143.957	-60.465	19.463	-128.117
a_5	17010.48	7892.295	-7283.796	12028.786
b_3	181.595	-114.671	25.341	-20.23
b_4	-0.165	-0.228	-0.065	0.043
c_3	34.85	37.241	-4.106	25.526
a_2	-0.642	-0.803	0.316	0.314
b_2	-244158.187	-233661.571	-395343.692	-409821.124
c_2	0.240	-0.03	0.097	-0.072
d_2	-7802.921	-1786.404	288.491	-1029.165
Correlation with experimental data	0.921	0.911	0.902	0.911
Maximum error,%	29.621	33.895	30.185	28.99

6.4.2. Grinded material quality study using statistical distributions

In this paragraph, the way of using objective quality function is described, deduced through smallest squares method using experimental data.

Coordinates of maximum point will be dependend on the *x* parameter, which gives command to the beneficiary, meaning the fragment maximum limit dimension. In other words, maximum point of coordinates ($d_{smax}(x)$, $v_{max}(x)$, $q_{max}(x)$, $P_{max}(x)$), *este dependent de x.*

Noting:

$$\Delta = \begin{vmatrix} 2b_2 & b_3 & b_4 \\ b_3 & 2c_2 & c_3 \\ b_4 & c_3 & 2d_2 \end{vmatrix} \qquad \Delta d_s(x) = \begin{vmatrix} -b_1 & -a_3x & b_3 & b_4 \\ -c_1 & -a_4x & 2c_2 & c_3 \\ -d_1 & -a_5x & c_3 & 2d_2 \end{vmatrix}$$
$$\Delta \nu(x) = \begin{vmatrix} 2b_2 & -b_1 & a_3x & b_4 \\ b_3 & -c_1 & a_4x & c_3 \\ b_4 & -d_1 & a_5x & 2d_2 \end{vmatrix} \qquad \Delta q(x) = \begin{vmatrix} 2b_2 & b_3 & -b_1 & -a_3x \\ b_3 & 2c_2 & -c_1 & -a_4x \\ b_4 & c_3 & -d_1 & -a_5x \end{vmatrix} \tag{6.16}$$

we obtain the following expressions for the maximum point coordinates (which maximizes the probability to obtain grinded fragments smaller than x:

$$d_{smax}(x) = \frac{\Delta d_s(x)}{\Delta}, \qquad v_{max}(x) = \frac{\Delta v(x)}{\Delta}, \qquad q_{max}(x) = \frac{\Delta q(x)}{\Delta} \tag{6.17}$$

Distribution of grinded material (the main product of the grinding or chopping process) is characterized, in general, statistically showing in which manner the mill succeeds inreducing geometrical dimensions of the processed material, sometimes trying to forecast distribution according to pricess command parameters. One of the static distributions that's widely used in these types of problems is the Rosin-Rammler distribution, used, for example, in [5].

After calculations from 4.1 sub-chapter, it is easy to take a Rosin-Rammler distribution into consideration like:

$$P(x, d_s, \nu, q) = 1 - exp\left[-\left(\frac{x}{a(d_s, \nu, q)}\right)^{b(d_s, \nu, q)}\right] \tag{6.17'}$$

in which *a* and *b* are considered command parameter functions:

$$a(d_s, \nu, q) = a_o d_s + a_1 \nu + a_2 q \qquad b(d_s, \nu, q) = b_o d_s + b_1 \nu + b_2 q \tag{6.17''}$$

Functions *a* and *b* can have the form (8'') or any other adequate form (there is an infinity of such possibilities).

In the case of hammer mill with one corner edges hammers. if the grinded material is Miscanthus, the following regression coefficient values are obtained: a_o= -0.793, a_1= 0.001 m·s, a_2= -0.132 m·s/kg, b_o=-0.574 m^{-1}, b_1= 0.04 s, b_2= 0.005 s/kg (rel.6.17').

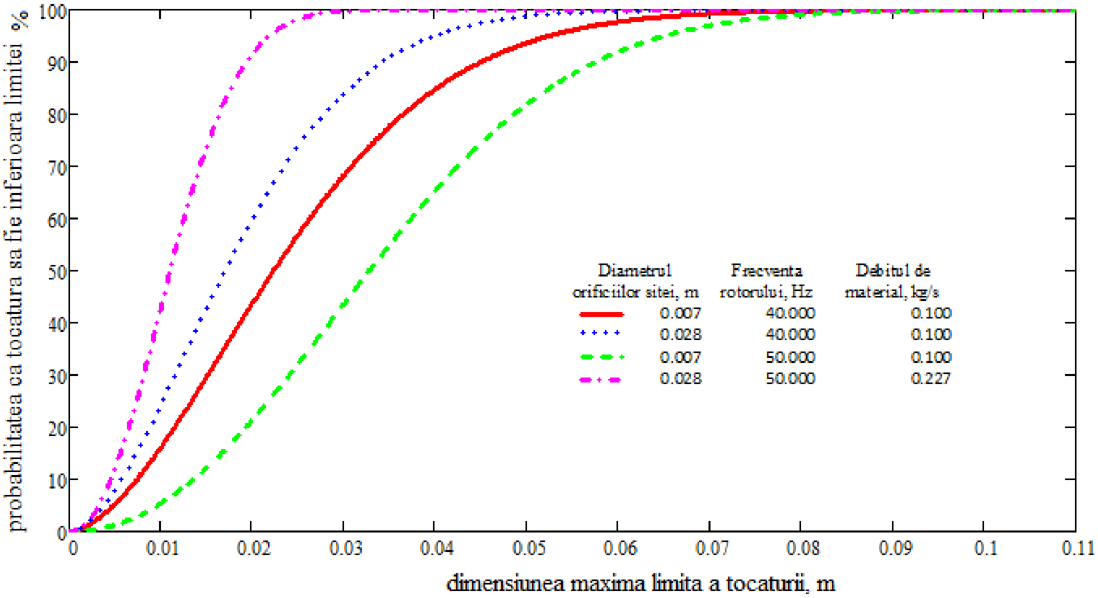

Fig. 6.3 Cumulative probability that the grinded material has length smaller than the limit dimension (for four combinations of command parameters)

Synthetic resunts for the other cases, in which Rosin-Rammler distribution parameters (6.17') and (6.17'') were calculated minimizing the functional (below), and are found in table 6.5.

$$\Omega(a_o, a_1, a_2, b_0, b_1, b_2) = \sum_{k=0}^{n} [M(x_i, d_{s.i}, v_i, q_i, a_0, a_1, a_2, b_0, b_1, b_2) - g_i]^2 \qquad (6.18)$$

Table 6.5 Statistical quality modelling through Rosin–Rammler distribution (rel. 6.18)

Tip ciocan	***a_o***	***a_1***	***a_2***	***b_o***	***b_1***	***b_2***
Miscanthus giganteus						
One corner edge	-0.314	0.001	-0.152	0.349	0.043	0.005
Two corner edges	0.389	0.001	-0.202	0.138	0.041	0.005
Three corner edges	-0.496	0.001	0.005	0.493	0.039	0.005
With oblique edges	-0.194	0.001	-0.065	0.689	0.045	0.005
Salix viminalis						
One corner edge	0.273	0.000	-0.011	1.000	0.055	0.007
Two corner edges	0.229	0.000	-0.003	1.000	0.056	0.007
Three corner edges	0.247	0.000	-0.006	1.000	0.054	0.010
With oblique edges	0.349	0.000	0.018	0.922	0.045	0.006

6.5. Grinding process optimization study regarding energy consumption

6.5.1 Estimating objective energetic functions for Miscanthus biomass

a. ***Second degree objective function in hypothetical combination (6.19).*** Although there is no such dependency resulted from statistical estimations from sub-chapter 6.2, an objective function for second degree energy variation is taken into consideration, of the type:

$$E = c_o + c_1 \frac{v\,q}{d_s} + c_2 \left(\frac{v\,q}{d_s}\right)^2 \qquad (6.20)$$

due to an intuition leading to this. For identifying coefficients c_o, c_1 și c_2, the smallest squares method is used, minimizing fhe functional:

$$\psi = \sum_{i=1}^{n} \left\{ c_o + c_1 \frac{v\,q}{d_s} + c_2 \left(\frac{v\,q}{d_s} \right)^2 - E_i \right\}^2 \qquad (6.21)$$

Cancelling the functional partial derivates (6.21), in relation to the three coefficients, we obtain the following concrete form for the objective energetic function (6.20):

$$E = E(v, d_s, q) = 407214.521 - 519.604 \frac{v\,q}{d_s} + 0.514 \left(\frac{v\,q}{d_s} \right)^2 \qquad (6.22)$$

Energy dependency curve (6.22) of the given combined argument in (6.19), is a parabola that has a minimum point, of coordinates:

$$\left(\frac{v\,q}{d_s} \right)_{min} = 480.625 \ \frac{kg}{m\,s^2}, \quad E_{min} = 282347.197\,J \qquad (6.23)$$

Values of minimum point coordinates can be verified also on the graph in fig. 6.4.

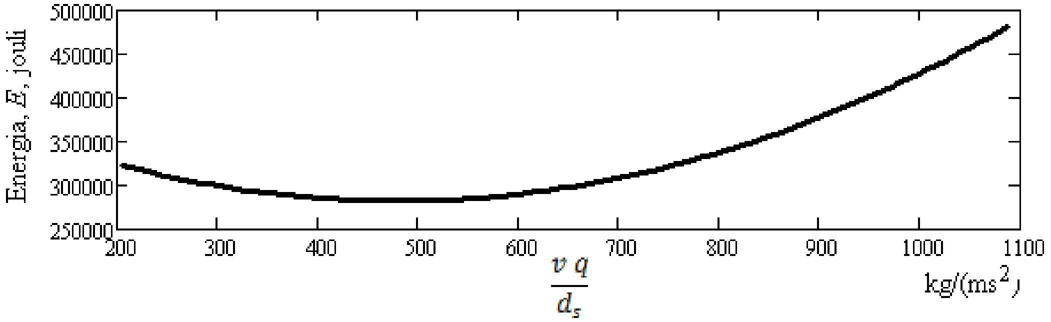

Fig. 6.4 Variation of objective energy function in relation to the argument formed in (6.19)

b. Second degree objective energy function in variables d_s, v și q. An objective function of the second degree polynomial form energetic type is proposed with three variables: sieve orifice diameter, rotor frequency and mass flow. For coefficients calculations the same method of the smallest squares for second degree polynomial objective function is applied:

$$E = E(v, d_s, q) = E_o + e_1 d_s + e_2 v + e_3 q + e_{12} v d_s + e_{23} vq + e_{13} q\, d_s + e_{11} d_s^2 + e_{22} v^2 + e_{33} q^2 \qquad (6.25)$$

$$E = E(v, d_s, q) = (1.353 - 64645 d_s - 0.063 v + 8.01 q - 0.61 v\, d_s - 0.003 vq - 0.179 q\, d_s + 1754.66 d_s^2 + 0.001 v^2 - 2.88 q^2) \cdot 10^6 \qquad (6.25')$$

In absolute value, the dominant coefficient belongs to the d_s^2 term, followed by the d_s term, and far behind are terms *q and* q^2. The rest of terms have insignificant terms in comparison. Still their influencein the value of the polynome isn't insignificant because frequency has values between 40 and 50 Hz, whilst the orifice diameter has values of between 0.007 and 0.025, and flow is between 0.104 și 0.357. Thus, the influence of every variable in the value of energy, on the adopted polynomial form through statistical hypothesis, is a more complicated problem.

Minimizing through numerical metods (using Mathcad software), leads, for the oblique edge hammers, to an working process coordinates included in the experimental threedimensional interval (d_{smin}=0.007 m, ν_{min}=40 Hz, q_{min}=0.357 kg/s) with a proper energy E_{min}= 29932.549 J.

c. Energetic function with parametric combination argument resulted from statistical interpretation. In this paragraph,a form for the consumed energy function in the grinding process is obtained, exactly like in paragraph 6.5.1, with one single given modification for the combination (6.19),we considered (6.27) combination:

$$E\colon\ \frac{v}{q\ d_s} \tag{6.27}$$

This combination is indicated by statistical rations from sub-chapter 6.2. Exactly like before, the following expression for energetic function is obtained:

$$E = E(v, d_s, q) = 265589.123 - 0.135\frac{v}{q\ d_s} + 0.00007686\left(\frac{v}{q\ d_s}\right)^2 \tag{6.28}$$

d. Statistical modelling of consumed energy through polytrope functions. One of the most used variants for experimental data statistical modelling is polytrope function modelling. The general form for polytrope functions is:

$$f(x_1, x_2, \dots, x_n) = a\prod_{i=1}^{n} x_i^{c_i}, \qquad x_i > 0,\ c_i \in R \tag{6.31}$$

The concrete form of polytrope function, for the mill equipped with one corner edge hammers, is:

$$E(v, d_s, q) = 2.002\ d_s^{a-0.175}\,\nu^{2.495} q^{c-0.918} \tag{6.34}$$

6.5.2 Estimating objective energetic functions for willow biomass

In this sub-chapter tables with synthetical results, obtained for willow stalks, after the same methodology as in the case of Miscanthus stalks.

The dominant coefficient, in all the four cases (table 6.8), is the d_s^2 term coefficient, followed by d_s and at great distance coefficients q *and* q^2.

Still their influence in the polynome value isn't insignificant because frequency has values between 40 and 50 Hz, whilst the orifice diameter has values of between 0.007 and 0.025, and flow is between 0.104 and 0.357. So the influence of each variable in the value of energy, on statistical hypothesis adopted polynomial form, is a much more complicated problem.

In table 6.8, performances of the modelled process are also shown, in optimum energy terms (minimum) and coordinates (adjustment parameters) of the optimal point. Three of the hammer variants show minimum points of close energetic values (between 20944 J and 127950 J): hammer with oblique corner edges and the hammer with two corner edges.

Tablel 6.8 Coefficients and energetic objective functions performance (6.25) for the four types of hammers used on willow grinding

$\times 10^6$	One corner edges hammer	Two corner edges hammer	Three corner edges hammer	Oblique edges hammer
E_o	-2.324	-0.678	1.972	-0.144
e_1	38.011	-34.6	-84.685	-5.706
e_2	0.115	0.055	-0.097	0.012
e_3	-1.627	-1.509	4.929	-0.537
e_{12}	-0.527	0.834	1.336	0.467
e_{23}	-0	-0	-0	0
e_{13}	0.032	0.011	-0.127	-0.042
e_{11}	-806.328	-421.372	941.138	-745.843
e_{22}	-0.001	-0.001	0.001	0
e_{33}	-0.671	0.599	0.605	3.352
Correlation with experimental data	0.963	0.944	0.940	0.959
Maximum error,%	13.463	10.982	20.431	20.083
Regression coefficient	0.928	0.891	0.884	0.919
$d_{s.min}$	0.016	0.021	0.009	0.016
v_{min}	40	62.388	50	40
q_{min}	0.417	0.665	0.444	0.332
E_{min}	65561.282*	127949.998	46173.837**	20944.201***

*Value which is a minimum on the frontier because the global extreme is obtained for negative flow

**Value obtained by minimization, on the domain frontier. Resulted critical point through cancelling equation system with partial derivates is not a point of extemum, but a saddle point.

***Minumum value situated on the frontier, obtained through numerical minimization. The obtained extremum point through cancelling partial devivates is not a minimum and is on the outside of the domain limited by extremes of experimental data.

6.6 Regression analysis for grinding biomass energetic function

In order to operate as compactly as possible and in the limits of standardized working algorithms confirmed through large utilization, we used the regression analysis algorithm from [21,47]. The complete calculation is given for the energetic function corresponding to the mill equipped with one corner edges hammer. Results are synthetically shown for the other seven examined cases. Initial necessary data for calculation are, like on other applied methods, experimental data vectors, independent variables, d_s, v, q, respectively the dependent variable E, meaning the consumed energy for the working process. Correlation between empirical data row (energies) and forecasted data row has the value of 0.882, maximum error: 38.8%.

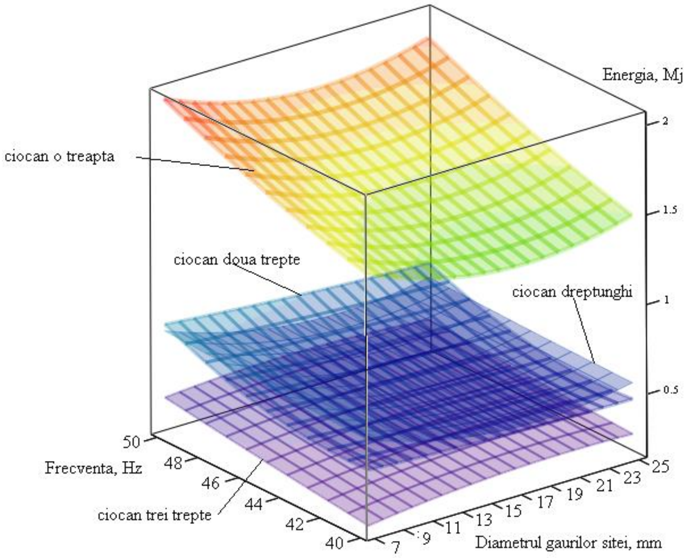

Fig.6.10 Representation as a surface in threedimensional space of the energetic function, as a partal function of sieve diameter size and frequency. Representation corresponds for the constant Miscanthus stalks flow equal to 0.166 kg/s.

In the case of regression analysis calculated energetic functions, the highest consumed energy values in the Miscanthus biomass grinding process, are obtained from using two corner edge hammers, but the rule isn't valid on the hole working interval.

Capitolul 7 - General conclusions; Contributions; Recommendations; Perspectives

7.1. General conclusions regarding theoretical and experimental researches

1. Grinding process has as main utilities: reducing harvested biomass volume and material preparation for the pellet production process. Speciality articles outline the fact that the ideal grinding degree differs according to the utilized material, both in energetic consumption from the pellet production process, as well as in the quality of resulted pellets. So, a high necessity regarding the study of different materials particularities is observed, passed through the pellet production technological flow.
2. Miscanthus is considered one of the main plants with high potential in pellet production material. Main attributes for this are: relatively cheap plantation, possibility of growing crops where other crops wouldn't survive, large quantity of produced biomass, and production of quality pellets.
3. Energetic willow – Salix viminalis is a willow with energetic characteristics, used in biomass production. Energetic willow, after Miscanthus, is the second plant regarding popularity in studies and speciality researches, due to its properties. Main attributes which make this willow a good source of biomass production are: growth of 3 – 3.5 cm/day, resistance to diseases and climate conditions, a caloric power of 5000 kca/kg, lifecycle of a crop is 25 - 30 years.

7.2. Personal and original contributions from the thesis

1. Regarding hammer shock equilibration, due to some identical dimensions for type A, B, C, D hammers, calculated values of l, c, and f are also identical;
2. A hammer mill working process mathematical modelling was realized, through dimensional analysis using the Π theorem. This analysis researched the aanticipation for the necessary power to action the mill both for Miscanthus and energetic willow;
3. Hammer mill working organ stress simulation was realized, through applying finite element simulation with the help of SolidWorks 2016 Premium. A maximum deformation of 0,036 mm was observed at the hammer tip due to centrifugal force during functioning.
4. Objective function that describes hammer mill working process quality, destined for vegetal material grinding was discovered. Formation of a function directly on the existent normalized data was tried, through interpolation of probability density. Interpolation produced unsatisfactory results (correlation between original data and interpolation obtained data was of 0.671, and maximum error of almost 65%). For these reasons, the same type of interpolation for the probability to obtain grains with smaller sizes than the x dimension was realized, proposed by the beneficiary. Function (6.14’) was obtained, and its correlation with experimental data was of 0.921, maximum error was 29.59%, considered acceptable values.
5. Starting from established Kick, Bond and Rittinger relations that describe grinding energy consumption, coefficients of these relations having real values (experimentally determined) were determined, for biomass grinding energy.
6. For Miscanthus biomass it was concluded that:
    - Type A hammer, at speed of 2550 rot/min, *coefficient* C_k has values between 21.68 kJ/kg for ϕ16 mm sieve and 29.66 kJ/kg for ϕ25 mm sieve,
    - *coefficient* C_R , from Rittinger relation, varies between 0.82 – 2.69 kJ·m/kg, in relation to the type of hammer and rotor speed, pentru sita de ϕ25 mm, respectiv 0.71 – 2.02 kJ·m/kg, pentru sita de ϕ16 mm, and between 0.45 – 1.34 kJ·m/kg for ϕ10 mm sieve,
7. For energetic willow we can say that:
    - *coefficient* C_B with value of 6.52 kJ·$m^{0,5}$/kg for type A hammer amd speed of 2400 rot/min and a minimum of 2.57 kJ·$m^{0,5}$/kg for type C hammer and speed of 2400 rot/min;
8. Grinded material distribution determination on dimension classes was realized, and it was correlated with Rosin – Rammler law.
9. Mill constructive paramenter influence degree was realized (sieve orifice size and hammer type) on grinding energy consumption and on grinded material quality.
10. Reffering to the hammer type influence on grinded average particle sizes for the ϕ25 mm sieve, a value variation in large limits for type A hammer (14 -23 mm) and for type B hammer (16 – 21 mm) was observed, compared to type C and D hammers for which particle dimensions were between 21 – 24 mm, respectively 22.5 – 24.5 mm.

11. For the case of using the ϕ16 mm sieve, grinded material particle size variation (salix viminalis) is presented within the limits of 9 – 12 mm, no matter what the rotor speed or hammer type are. Highest degree of grinding was given by type A hammer, at speed of 2850 rot/min, and the lowest grinding degree was given by type D hammer, at speed of 2700 rot/min.

7.3. Recommendations and future perspectives for research

For future research activities we recommend:

1. Continuation of researches regarding hammer mill working process through hammer mill testing using other types of biomass for correlating future data reffering to the influence of different hammer mill constructive and functional parameters on energetic consumption and on grinded material quality.
2. Resolving hammer and rotor equilibration problems for ensuring a uniform functioning;
3. Continuation and expanding researches regarding energetic plant behavior during grinding process;
4. Realizing some work models for the biomass grinding process, through modelling and simulation analysis, regarding hammer mills working process.

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English	A2	Experienced user	A2	Experienced user	A2	Experienced user	A2	Experienced user	A1	Experienced user
	(*) Foreign European languages reference level (Nivelul Cadrului European Comun de Referinţă Pentru Limbi Străine)									