ASPECTS REGARDING GRINDED *SALIX VIMINALIS* DISTRIBUTION AND ENERGY CONSUMPTION USING HAMMER MILL

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Abstract. In the recent years, the interest in renewable energy resources has increased because of the rising energy demand and fuel costs, environmental concerns and limited sources of fossil fuels. Energy crops are frequently used in the production of environmentally friendly fuels such as: pellets and briquettes, biogas, biodiesel and bioethanol. Pelleting and briquetting processes have been used for many years to produce densified biomass for fuel applications. Pelletizing of biomass involves grinding, conditioning by applying heat and/or moisture, and forcing the sample through die. The main parameters that influence the pelleting process are the particle size, preheating temperature and die rotational speed. Particle size of the feedstock influences the binding phenomena as smaller size particles have more surface area or contact area and facilitate better binding. In the present paper, using *Salix Viminalis* as biomass, the grinding process was analyzed using a hammer mill MC 22 equipped with different sieve orifice diameter (Ø7 mm and Ø10 mm), four types of hammers and the rotor speed ranged from 2400 rpm to 3000 rpm. The energy consumption necessary for the grinding process was researched and compared between the two types of sieves in order to obtain lower energy consumption for milling. The distribution of grinded *Salix Viminalis* for each type of hammer taking into consideration the rotor frequency is also presented. In the paper, the results obtained present, which hammer can be regarded as an optimum for a certain value of rotor frequency.

Keywords: biomass grinding, hammer mill, energy consumption, rotor frequency.

Introduction

Lately, decreasing greenhouse gas emissions to the atmosphere and the independence of global economy from fossil fuels are the main arguments to use renewable resources for energy production [1]. Lignocellulosic crops like *Miscanthus* (*Miscanthus x giganteus*) and willow (*Salix viminalis*) can have an interesting future as energy crops in European countries [2]. One of the major limitations of using biomass as a feedstock for bioenergy products is its low bulk density, which typically ranges from 80-100 kg·m^{-3} for agricultural straws and grasses and 150-200 kg·m^{-3} for woody resources like wood chips and sawdust. In order to overcome this limitation, the biomass density must be increased [3]. Pelleting and briquetting processes have been used for many years to produce densified biomass for fuel applications. Pellets are made from biomass that is hammer milled into fine pieces and then processed into cylindrical pellets under high pressure and temperature [4]. Size reduction is an important stage in the pelleting process. It influences a range of parameters, such as compaction, contact between particles and friction in the die [5]. In literature, the majority of researches in pelleting process use a hammer mill screen size between 0.5 and 8 mm and a size limit of 5 mm is suggested [6; 7].

Găgeanu et al. investigated the process of pelleting *Salix Viminalis* depending on the humidity and granulation. They concluded that the best pellets in terms of humidity, length, surface characteristics, calorific power and ash content were obtained for the particle size of about 3 mm and humidity of 9 % [8].

Noorfidza and Muhammad [9] also reported that the particle size contributes to the mechanical strength of biomass pellets: biomass pellets made with a smaller particle size showed high yield stress and density. They tested the particle size of biomass in range of 150-300, 300- 425 and 425-600 μm.

The specific energy requirements for biomass densification depend on many variables, such as: process variables: temperature and pressure, feedstock variables: moisture content and particle size and also biochemical composition variables: presence of starch, protein and lignocellulosic biomass composition [10].

The aim of the present paper was to determine the energy consumption necessary for willow (*Salix Viminalis)* grinding using a hammer mill type MC-22 equipped with a sieve with different orifice sizes (Ø7 mm and Ø10 mm), four types of hammers and the rotor speed ranged from 2400 rpm to 3000 rpm.

Materials and methods

Experimental research was conducted using shredded biomass of energetic willow (*Salix viminalis)* at harvest, which was subjected to a milling process using a hammer mill type MC-22. The grinded energetic willow had the particle size between 25-47 mm. The biomass moisture at the time of the milling process ranged between 8.89-11.99 %. The hammer mill type MC-22 (Fig. 1) is equipped with a 22 kW electrical engine and has a milling capacity of 0.22-0.42 kg^{-1}, the rotor length is 500 mm, the diameter of the hammers disposal is Ø220 mm and the grinding chamber diameter is Ø500 mm.

Fig. 1. **Hammer mill MC 22:** 1 – hammer mill; 2 – exhauster; 3 – cyclone with support and dust collector bag; 4 – grinding material evacuation vent; 5 – electric motor

During the experimental research, interchangeable sieves with orifice sizes of Ø7 mm and Ø10 mm were used and the rotor speed ranged from 2400 rpm to 3000 rpm (in steps of 150 rpm). The material was grinded through hitting and shearing between hammers mounted on the hammer disk and counter knives. The hammers used in the experiments had several shapes, such as: A – with an edge; B – with two edges; C – with three edges and D – with bevelled corners. During the milling process, the required energy consumption was determined depending on the hammer type, the rotor speed and also the used sieve. The biomass quantity subjected to the milling process was 4 kg, the grinding time being variable.

The grinded biomass was then subjected to a granulometric sorting process using the sieves of a classifier type AS 200 basic, the grinding time being about two minutes. The sieves had holes of 4, respectively 7 mm in the case of a Ø7 mm sieve and of 4, 7, respectively 10 mm for a Ø10 mm sieve.

Results and discussion

The obtained results after the experimental research are presented in Table 1.

Table 1

Variation of grinding energy depending on the hammer mill parameters

Sieve holes diameter mm	Rotor frequency rpm	Hammer type A, kJ·kg^{-1}	Hammer type B, kJ·kg^{-1}	Hammer type C, kJ·kg^{-1}	Hammer type D, kJ·kg^{-1}
10	3000	42.809	34.120	47.559	36.851
10	2850	40.255	33.422	47.326	30.553
10	2700	35.696	29.168	27.934	26.936
10	2550	45.534	35.949	29.647	23.906
10	2400	49.572	28.371	40.545	35.522
7	3000	40.959	33.434	57.755	33.942
7	2850	57.615	35.083	51.149	27.591
7	2700	30.738	29.649	26.179	34.860
7	2550	42.295	47.729	38.873	42.205
7	2400	27.171	45.044	40.117	36.196

The grist factions have been reported to the sample amount of material and the obtained percentages have been processed using MS Excel. In Table 2 and Table 3, the material percentages on each of the classifier sieves depending on the hammer type and the hammer mill speed, are presented. Based on the results from Table 2 and Table 3, the distribution curves of the grinded material were plotted depending on the rotor speed and on the used hammer type, for the two sieve types of the grinding chamber. As it can also be observed in Figure 2, the five points used in order to graphically represent the experimental data represent each speed of revolution (2400, 2550, 2700, 2850 and 3000 rpm).

Table 2

Experimental results regarding the grinded material size distribution for the mill sieve of 7 mm

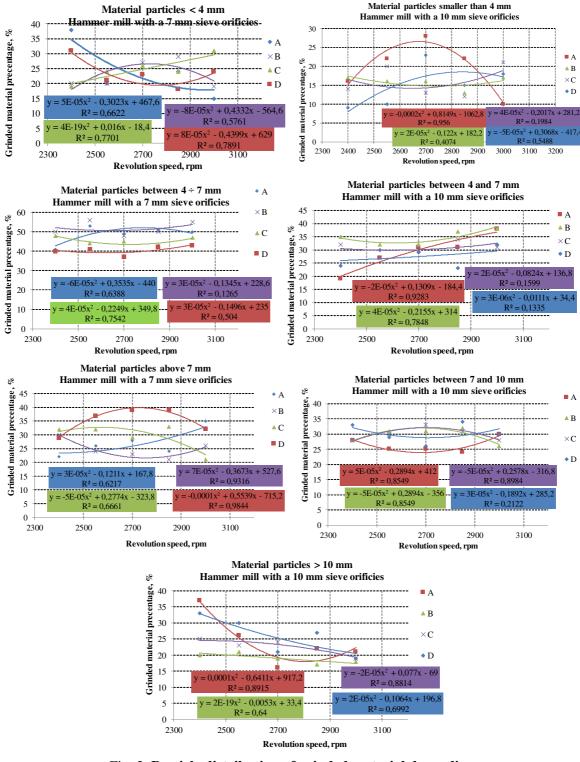| Rotor speed rpm | Percentage of material on the sieve, % | | | | | | | | | | | |
| | Particles size < 4mm | | | | Particles size between 4-7 mm | | | | Particles size > 7 mm | | | |
	A	B	C	D	A	B	C	D	A	B	C	D
3000	15	19	31	24	50	55	47	43	35	26	21	32
2850	24	29	24	18	51	50	43	42	24	21	33	39
2700	23	27	26	23	49	48	45	37	28	23	29	39
2550	20	20	24	21	53	56	44	41	26	24	32	37
2400	38	20	19	31	41	50	48	40	22	30	32	29

Table 3

Experimental results regarding the grinded material size distribution for the mill sieve of 10 mm
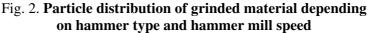
| Rotor speed rpm | Percentage of material on the sieve, % | | | | | | | |
| | Particles size < 4 mm | | | | Particles size between 4-7 mm | | | |
	Hammer type A	Hammer type B	Hammer type C	Hammer type D	Hammer type A	Hammer type B	Hammer type C	Hammer type D
3000	10	17	21	18	38	38	31	32
2850	22	13	12	15	31	37	34	23
2700	28	16	13	23	31	32	30	29
2550	.22	16	20	10	27	32	27	30
2400	16	17	14	9	19	35	32	24
	Particles size between 7-10 mm				Particles size > 10 mm			
	Hammer type A	Hammer type B	Hammer type C	Hammer type D	Hammer type A	Hammer type B	Hammer type C	Hammer type D
3000	30	26	28	30	21	18	19	19
2850	24	32	31	34	22	17	22	27
2700	25	31	33	26	16	19	24	21
2550	25	31	30	29	26	21	23	30
2400	28	28	28	33	37	20	25	33

As it can be seen from Table 2 and the graphs in Figure 2, the highest percentage of material particles for the mill sieve with the orifice sizes of Ø7 mm was recorded for 4 and 7 mm fractions. At the same time, if analyzing the distribution of the material on the sieves, we observe the highest percentage of grinded biomass for the A and B hammer type and particles between 4 and 7 mm. The correlation coefficient in the variation graphs has the highest value for the hammer type D for material particles larger than 7mm.

For the mill sieve with the orifice sizes of 10 mm, as shown in Table 3 and Figure 2, the highest percentage of material, regardless of the hammer type, was recorded for the material particles between 4 and 7 mm, and the lowest for material particles less than 4 mm. Also, from the variation graphs it can be seen that the highest correlation coefficient R^2 was obtained for the A hammer type ($R^2 \geq 0.85$).

If we analyse the distribution of the grinded material in terms of the rotor speed, it was noticed that for the speed of 3000 rpm the highest percentage of material was recorded for the particle sizes between 4-7 mm, both for the sieve with orifice sizes of Ø7 mm, and for the sieve with orifice sizes of Ø10 mm. For each sieve curves obtained after the experimental research a polynomial regression analysis was done. This regression was chosen in order to best fit all curves; another type of regression analysis did not apply to every set of values and needed to be changed each time when a hammer of a sieve was chosen for analysis. The equation coefficients can be observed in Figure 2 for every parameter.

Fig. 2. **Particle distribution of grinded material depending on hammer type and hammer mill speed**

For a more accurate exemplification of the energy consumption variation resulting in the milling process, the energy consumption variation for each type of sieve depending on the hammer type was plotted using the Microsoft Excel program.

If the variation of the energy consumption is analyzed, it can be seen that higher values were recorded for the sieve with orifice sizes of 7 mm, compared to the sieve with orifice sizes of 10 mm. The lowest energy consumption was recorded for the D hammer type at the speed of 2550 rpm in the case of the 10 mm sieve, and the highest consumption was recorded for the sieve of 7 mm, the A hammer type and the speed of 2850 rpm.

Also, from Figure 3 a variation of the specific energy consumption approximately between the same values for both sieves in the case of the D hammer type can be noticed. Similarly, if we analyze the energy variations for the C hammer type, higher values are observed for high speeds, average values of the energy consumption for lower speeds, and for the speed of 2700 rpm the lowest energy value in the both cases is found. Excepting the D hammer type, average energy consumption for 2700 rpm speed for both sieves used can be noted. The highest energy consumption values, in both cases, were recorded in most cases (hammer type) for 2850 rpm.
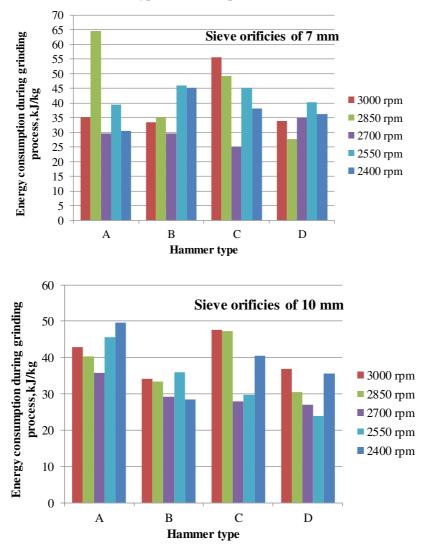

Fig. 3. **Energy consumption variation depending on rotor speed**

Conclusions

1. Comparing the grinded material percentage for both sieves it can be said that for the sieve with the orifice sizes of Ø7 mm the values are between 15-56 % and for the sieve with the orifice sizes of Ø10 mm the values are between 9-38 %.

2. A percentage of grinded material distribution was established as being lower for material sizes below 4 mm and over 7 mm, with the values between 15-38 % respectively 21-39 % comparing to the material sizes between 4 and 7 mm, which had a percentage of material between 37-56 % for tests done with a sieve of Ø7 mm.

3. The correlation coefficient obtained by analysing the variation of material quantity by size classes recorded higher values for the A (R2 above 0.62) and D hammer type (highest value recorded for R2 being 0,98 for particles higher than 7 mm), for the sieve with the orifice sizes Ø7 mm,

4. Considering the correlation coefficient for the sieve with the orifice sizes of Ø10 mm it must be said that R2 had for the hammer type B a value of 0.85 and for the hammer type A all correlation coefficients were above 0.85.

5. Instead, the energy consumption recorded for Salix Viminalis biomass grinding showed a higher value for the sieve with orifice sizes of Ø7 mm, respectively 64.52 kJ·kg^{-1}.

6. Depending on the hammer type, the lowest energy consumption was recorded for the C with the values between 26.17-57.75 kJ·kg^{-1}, respectively, the D hammer type with the values between 23.9-36.85 kJ·kg^{-1}, for the sieve with orifice sizes of Ø7 mm, respectively 10 mm.

7. For medium speeds of 2700 rpm, medium energy consumption around 30 kJ·kg^{-1} was recorded for grinding for both types of sieves and approximately for all hammer types.

8. Following the experimental research, for each speed value, a certain type of hammer considered optimal can be indicated (for example, for speeds of 2700 rpm and 2850 rpm, it is indicated to use a three-step hammer for minimal energy consumption).

Acknowledgements

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