THEORETICAL AND EXPERIMENTAL RESEARCH ON THE PROCESS OF BIOMASS BRIQUETTING

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Biomass represents the biodegradable part of products, waste and residues from agriculture, forestry and, implicitly, from industrial and urban waste. Briquetting is the process of compaction through biomass densification by approximately 80 to 90%, in order to obtain finished products (briquettes, pellets, etc.) with increased and homogenous density, regular shape, used as fossil fuel. Theoretical research of the briquetting process has as goal to establish the theoretical link between the quality parameters of products, the control-command parameters and the initial parameters of the raw material. Experimental research has as goal to further check or adjust the mathematical model predicted.

Keywords: biomass, briquetting, sawdust, mathematical model.

1. Introduction

Biomass is considered one of the main forms of renewable energy. Current statistics show that emerging countries cover about 38% of their own energy needs with biomass, and in many of these countries, burning fire wood represents up to 90% of the total energy consumption [1]. Also, some developed countries currently ensure for themselves, from biomass, an important share of their own energy consumption, such as 18% in Finland, around 14% in Sweden, 10% in Austria, etc. Biomass, which represents around 15% of the primary energy sources used worldwide [2], does not contribute to the increase of CO_2 concentration in the atmosphere, but it contributes to the reduction of the

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greenhouse effect and does not produce acid rains, thanks to sulfur content lower than to one existing in the structure of fossil fuels. Therefore, biomass is the ensemble of non-fossil organic matter in which are inscribed: wood residues, agricultural residues, plant residues from the forestry sector, but also cereals and fruits [3]. The main difference between the energy obtained from classic fuels and respectively biomass is the following one: fossil fuels can only be transformed into usable energy after thousands of years, whereas the energy from biomass is renewable and it can be used every year.

Biomass in its original form is difficult to be used successfully as fuel in large scale applications, because it is bulky, wet and dispersed. Compaction technologies are used for converting biomass (agricultural and forestry residues) into fossil fuels. These technologies are also known under the name of briquetting, pelleting, granulation, molding, packing, etc. [4]. Briquetting and pelleting are the most common processes used for biomass compaction in order to satisfy the demands for solid fuel.

The process of compacting biomass during briquetting can be attributed to plastic and elastic deformation of particles at high pressures. According to studies conducted until now, the important aspects that are to be taken into consideration during the process of compaction are [5]:

1. The capacity to form briquettes with a considerable mechanical resistance;
2. The capacity to increase the density of the process.

The possible binding mechanism during agglomeration can happen due to the formation of the so called solid punctures [6, 7]. During compaction, these solid punctures are developed by the numerous chemical reactions, binder hardening, solidifying of melted substances or crystallizing of dissolved materials. Pressures applied during densification (compaction) also reduce the particle melting time and make them move towards each other, thus increasing the contact area and changing the melting time to a new balanced level [8].

Briquetting and pelleting technologies used for biomass densification in order to satisfy demands for solid fuel are performed at high pressure and are usually carried out using a screw or piston press [9]. In the screw press, biomass is contiguously extruded through a heated cone shaped mold [10].

Briquettes obtained using a screw press has a much better quality compared to the ones from a piston press. However, comparing the wear degree of the parts in a piston press to the ones in the screw press, the wear of the piston press is much more reduced [11]. Many researchers have studied the process of compacting herbaceous and woody biomass in order to obtain briquettes using mechanical presses with screw or with piston [12, 13].

In order to optimize the process of briquetting biomass, researchers have elaborated a series of mathematical models for compaction [14, 15, 16]. They help to reveal the behavior of biomass/particles during the process of compaction (briquetting) and can help optimize the pressures necessary for obtaining good quality pellets/briquettes.

According to researches, it was noticed that during the compaction of oak sawdust, when increasing the pressure applied during the pelleting process from 0.24 – 5.0 MPa, good briquette densities are obtained even when the material has a humidity content of 10.3% [17, 18]. They have also noted an obvious increase in the density of the briquettes when increasing the pressure inside the pressing chamber above 3 MPa [2]. The quality of briquettes is influenced significantly by the retention times or the retention time of the material in the mold. The research conducted has found that retention times situated between 5 and 20 seconds did not have a significant effect on the durability and stability of briquettes [19]. The retention time for oak sawdust had a greater effect at lower pressures than at high pressures. At the biggest pressure value (138 MPa), the effect of the retention time became negligible. They have also noticed that the retention time had a pretty low effect on the expansion rate, and that the retention time had more effect at lower pressures. It appears that retention times higher than 40 seconds had a negligible effect on density [20, 21]. A retention time of 10 seconds could lead to a 5% increase of density, while at 20 seconds the effect is diminished considerable.

Humidity present in biomass facilitates starch gelatinization, protein denaturation and the processes of solubility during fiber extrusion [20]. It was noted that the humidity contained by the biomass during the process of compaction acts as a binder and increases the degree of joining through the means of Van der Wall forces, thus increasing the contact area between particles [2, 7, 9]. It was found that by increasing the humidity content of spruce sawdust from 7 to 15%, the durability of pellets obtained increases significantly [2, 3, 8].

2. Materials and methods

Starting from a raw material consisting of sawdust from forestry residues, with various granulations and humidity, was aimed to obtain cylindrical briquettes in a mold, by pressing the material with a piston.

At the beginning of the compression process, the outlet end for the compressed biomass is kept closed until it reaches a limit pushing pressure of the piston, afterwards the outlet is opened, allowing to release (evacuate) the formed briquette. For driving the piston, a force machine with a maximum capacity of 100 kN was used. The force machine used as compaction system, with the assistance of a computer, allowed to control the movement speed of the piston, and, respectively, to record the force-movement diagram (Fig. 1).


Fig. 1. Force machine used in the process of compacting biomass

The mass density of the input material (raw material, sawdust) is about 159-160 g/m^3. This sawdust results from various methods of processing wood, being possible to have significantly different granulations, from powders to wood chips. Dust was introduced in the briquetting process having a humidity of 10% up to 14%, at a constant temperature of 15^o C. The length of the initial column of material was 0.3 m, with a total mass of 0.06 kg. The mass of the processed material is preserved during briquetting.

In the carried out briquetting experiments the following parameters were varied: the pressing force (implicitly the pressure of the piston), the loading speed, the granulation of the material and its humidity. Final pressing forces ranging between 70 and 90 kN were reached. The piston's forwarding speeds were ranged between 0.00167 and 0.005 m/s. The pressing force of the piston and its forwarding speed were the two parameters used for controlling the process.

Theoretical researches had the purpose of establishing calculus relations that link the outlet parameters to the inlet and control parameters, briefly presented in table 1.

Table 1.

Parameters of the briquetting process

Inlet parameters	**Control parameters**	**Outlet parameters (quality)**
Humidity of raw material	Compaction force	Briquettes density
Density of raw material	Initial length of the material column	Briquettes durability
Granulation of raw material	Piston speed of movement	Capacity of maintaining cohesion
Mold temperature		

One of the most important problems in background a technology is that of establishing theoretical links between the quality parameters of products and the control-command parameters and, possibly, the initial parameters of the material. Graphic representations directly on the experimental data are not recommended, due to high number of experiments that were conducted (over 60) and of the parameters that were varied (4); for the same reason, sorting by category is not recommended. In this respect, it is recommended to perform a simple statistic characterization of the experimental data, followed by interpolation and graphic representations of the functions obtained by interpolation.

The first conclusions on the link between various categories of parameters can be obtained by studying the correlations between control parameters and quality or efficiency parameters. A list of the values of the correlation between the experimental vectors of the command parameters (force and piston movement speed) and the quality vectors for the process (density, hardness at the upper and at the lower part of each briquette, and their relaxation after 0-60 days) are given in table 2.

Table 2.

Values of the correlation between the experimental vectors of initial, control and command parameters and the quality vectors for the process

	Density	**Hardness at the upper part**	**Hardness at the lower part**
Pressing force	0.340	0.204	0.265
Piston movement speed	0.120	0.105	0.156
Granulation	-0.582	-0.596	-0.557
Humidity	0.065	-0.156	-0.079

One of the most important objectives of the authors was that of finding a calculus formula (or more) that will establish o link between the inlet and the outlet parameters of the briquetting process. In other words, the main purpose of the theoretical study is the mathematical modeling with applied purpose of the briquetting process. The end of the mathematical model is constituted by its use in the command and control of the process in the purpose of achieving an optimal process in a broad sense, meaning to achieve a product of satisfactory quality with minimum energy consumption. For the time being, the mathematical model is built after the elementary experiments and it will evolve in time, but any upper model will have to include this elementary model if it is valid.

3. Results and discussion

The process of biomass briquetting is a process defined by many random factors, a process that takes place on a material initially hard to place in a category (solid, gas, etc.). In addition, the material changes its density throughout the process, and such processes are less modeled in literature, the change of density being major, increasing by 6-7 times until the end of the process.

As a result of these physical aspects of the briquetting process, which basically represent a process somehow in reverse to the one of destroying wood by chopping or chipping, a process that is irreversible in nature, so mathematical modeling through classic models of mechanics or thermodynamics is practically very hard to access. Knowing the rheological behavior of the powder, determining the constitutive equation would require itself an extensive and costly experimental study. Moreover, once determined an approximate constitutive equation, there is the possibility that it is useless due to the complex shape or to the instabilities generated by its presence in the numerical processes of solving the mathematical model.

For the reasons above, we resorted to a simple model, proposing a mathematical relation of the form:

$$\rho = \rho_0 \left(\frac{F + F_0}{F_0} \right)^{\alpha} \left(\frac{v + v_0}{v_0} \right)^{\beta} \left(\frac{\phi}{\sqrt{rh}} \right)^{\gamma} u^{\eta} \tag{1}$$

where:

- ρ (in kg/m^3) is the current density of the briquette,
- ρ_0 (in kg/m^3) is the initial density of the raw material for briquettes,
- F (in N) is the pressing force,
- v (in m/s) is the piston's speed of movement,
- ϕ is the granulation (in m),
- u is the humidity of the material (in decimal fractions),
- $\alpha, \beta, \gamma, \eta$ are dimensionless exponents,
- F_0 (in N) and v_0 (in m/s) is the parameters of the process in the purpose of relativizing the product factors (1) corresponding to powers α and β.

Relativization is performed to allow exponents α and β to take real values without affecting the dimensional consistency of the formula. In case of F0 the expression of the gravity force of the sawdust powder mass introduced in the process was taken, while in case of v0 the value of the speed of a powder particle in a resistant environment that is the powder itself was considered:

$$F_0 = mg, \ v_0 = 0.1 \tag{2}$$

where:

- m is the mass of powder introduced in the process,
- g is the local gravitational acceleration,
- h is the height of the sawdust column initially introduced in the pressing tube.

Using the experimental results and minimizing the function:

$$\Im(\alpha,\beta,\gamma,\eta) = \sum_{i=1}^{N} \left(\alpha \ln\left(\frac{F_i + mg}{mg} \right) + \beta \ln\left(\frac{v_i + v_0}{v_0} \right) + S_i \right)^2, \ S_i = \gamma \ln \frac{\phi_i}{\sqrt{rh}} + \eta \ln u_i + \ln \rho_0 - \ln \rho_i \tag{3}$$

where:

- N (in this case 60) is the number of briquetting experiments conducted, and *ln* is the symbol of the natural logarithm, are obtained for the four exponents the values: α= 0.138, β= 0.396, γ= -0.074, η= 0.038. These exponents are dimensionless.

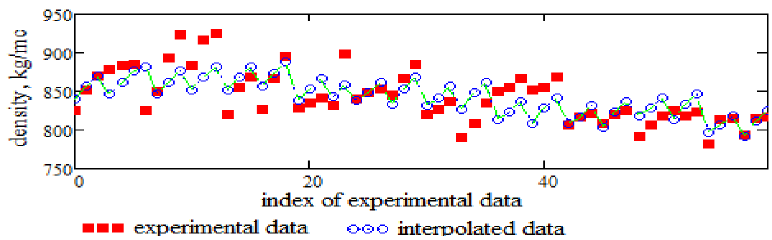

Fig. 2. Distribution of interpolated data in relation to experimental ones

The distribution of interpolated data using the method of the least squares as it was described above, in comparison to the experimental data, is shown in Fig. 2. If it is taken into consideration that:

$$m = \pi r^2 h \rho_0 \tag{4}$$

Than formula (1) can be written in a form that also explains the contribution from the geometry of the compression cylinder:

$$\rho(F, v, \phi, u, \rho_0, r, h) = \rho_0 \left(\frac{F + \pi r^2 h \rho_0 g}{\pi r^2 h \rho_0 g} \right)^{\alpha} \left(\frac{v + v_0}{v_0} \right)^{\beta} \left(\frac{\phi}{\sqrt{rh}} \right)^{\gamma^{\gamma}} u^{\eta} \tag{5}$$

Thus, the density function of the briquette becomes a function of the following parameters: (1) process and control parameters (F and v); (2) parameters of the initial material (ρ_0, ϕ , and u); (3) design parameters of the cylinder in which the compression process takes place (r – the cylinder radius, and h - the height of the initial column of material). If, through the surface of the piston one divides the numerator and the denominator of the factor to the α power, then the final density can be expressed as function of the current pressure on the upper surface of the briquette:

$$\rho(F, v, \phi, u, \rho_0, r, h) = \rho_0 \left(\frac{p + h\rho_0 g}{h\rho_0 g} \right)^{\alpha} \left(\frac{v + v_0}{v_0} \right)^{\beta} \left(\frac{\phi}{\sqrt{rh}} \right)^{\gamma^{\gamma}} u^{\eta} \tag{6}$$

where p is the pressure exerted by the piston on the upper surface of the briquette that in forming.

A function of the same type can be obtained for the hardness of the briquette, both for the one in the upper part and also for the one in the lower part.

A similar result can also be obtained for Shore hardness at the upper or the lower part of the briquette. Thus, for the hardness at the lower part of the briquette, the following formula is obtained:

$$\delta_i\left(F,v,\phi,u,\rho_0,r,h\right)=d_{0i}\left(\frac{F+\pi r^2 h\rho_0 g}{\pi r^2 h\rho_0 g}\right)^{\alpha i}\left(\frac{v+v_0}{v_0}\right)^{\beta i}\left(\frac{\phi}{\sqrt{rh}}\right)^{\gamma^{\gamma i}} u^{\eta i} \tag{7}$$

where:

- $\alpha i, \beta i, \gamma i, \eta i$ are the dimensionless exponents calculated using the method of the least squares like in the case of the calculus formula for the density of the briquette, (5),
- δ_i is the hardness of the briquette at the lower part,
- d_{0i} is the average experimental value of the Shore hardness on the lower part of the briquette.

The values of the four exponents of formula (7) are: –0.081, 1.07, –0.127, 0.0001414, and the average value of the experimental hardness d_{0i}, is 80.967 degrees Shore. For the hardness at the upper part of the briquettes obtained from sawdust, a formula similar to (7) is obtained, the exponents taking in order the following values: –0.118, 0.747, –0.183, –0.066, and the average experimental value, which appears in the first factor, 72.417 degrees Shore.

Comparisons between experimental data and the data interpolated according to the formulas above, for the lower and upper hardness, can be estimated by graphic representations in Fig. 3 and Fig. 4.

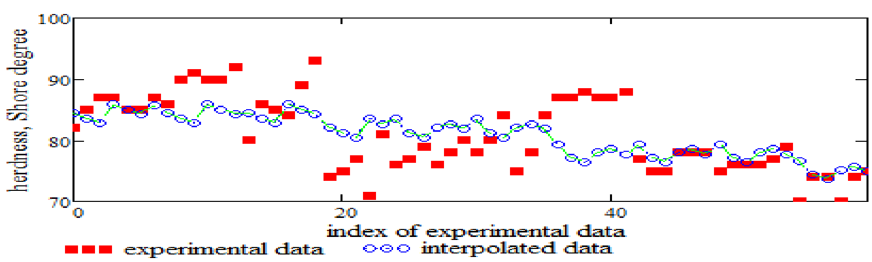

Fig. 3. Distribution of the data interpolated in relation to experimental ones, for the hardness of the briquette at the lower part

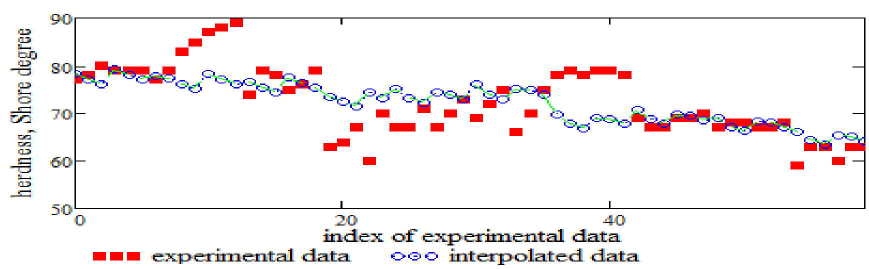

Fig. 4. Distribution of the data interpolated in relation to experimental ones, for the hardness of the briquette at the upper part

In order to understand the variation manner for the quality parameters for the compaction process, a few graphic representations are useful. In Fig. 5÷11 are given, one at the time, the dependencies of the average final density of the briquette to the parameters: *F, v, r, h*, ϕ, *u* and ρ_0. The dependencies are represented graphically for the extreme values of the pressing force achieved during experiments, this force representing the main command parameter, the most influential.

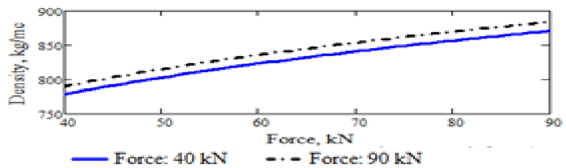

Fig. 5. Variation of the average final density of the briquette with the force of pressing the material in the cylinder

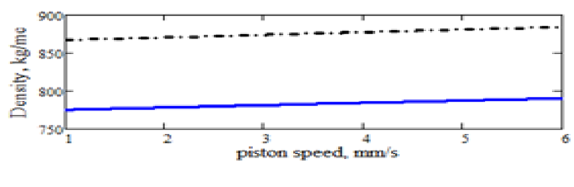

Fig. 6. Variation of the average final density of the briquette with the piston's movement speed

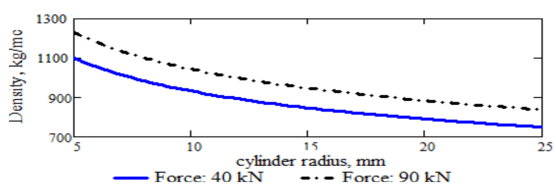

Fig. 7. Variation of the average final density of the briquette with the cylinder radius

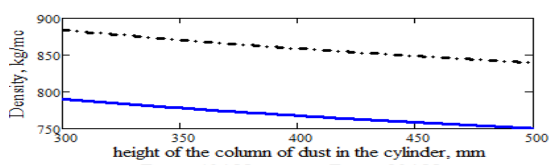

Fig. 8. Variation of the average final density of the briquette with the height of the cylinder

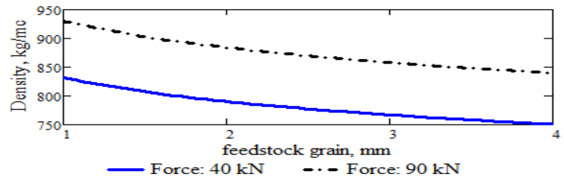

Fig. 9. Variation of the average final density of the briquette with the granulation of the raw material

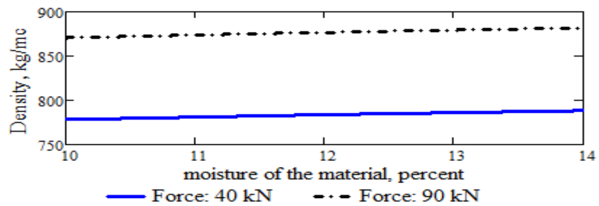

Fig. 10. Variation of the average final density of the briquette with the humidity of the raw material

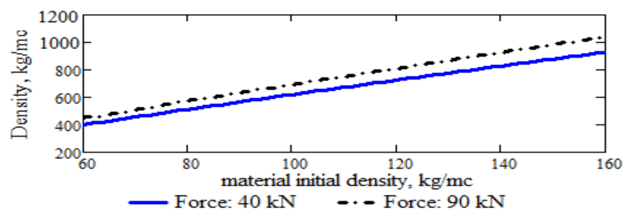

Fig. 11. Variation of the average final density of the briquette with the initial density of the raw material

4. Conclusions

Therefore, the technological process of obtaining briquettes (from sawdust) is possible to be mathematically modeled by models linking the input parameters (density, granulation and moisture of the raw material) with the qualitative output parameters (density of briquettes, hardness and loosening in time) and with the geometry of the mold for forming briquettes (cylinder diameter, height of the column of material), respectively with the process control parameters (pressing force and movement speed of the piston).

The values of correlations (table 2) show that:

- The pressing force is the main active parameter in the process of forming the briquette.
- Density and hardness acquired in the compaction process are directly depending on the pressing force.
- The movement speed of the piston is a parameter less liked to the quality parameters, but still significant.
- Granulation is little involved, but the correlations show that its increase leads to lower quality briquettes, and the humidity is also significantly involved in the final quality of briquettes.

According to the experimental data obtained and represented in figures 5 and 6, the determined functions of interpolation show that the density of briquettes varies almost linearly in relation to the force, but also with the piston's speed of movement. Thus, at a pressing force of 40 kN we have an average density of 781 kg/m^3 while for a force of 90 kN, the average density of briquettes was 889 kg/m^3. The final density of the briquettes formed decreases with the increasing of the pressing cylinder radius and with the increase of the height of the material column subjected to pressing (Fig. 7 and 8). According to the data, in case of a pressing cylinder with a radius of 15 mm and a pressing force of 40 kN, an average briquettes final density of 905 kg/m^3 is obtained, while for a force of 90 kN, the average density of briquettes is 1075 kg/m^3. The final density of briquettes also decreases with increasing the granulation of the raw material used, as shown in figure 9. Thus, for a granulation of 2 mm of the raw material and a pressing force of 90 kN, the average final density of the briquettes was 905 kg/m^3. Similarly, the final density of the briquettes increases slowly with the humidity and rather obvious in relation to the initial density of the raw material (Fig. 10 and 11). Thus, from an initial density of the raw material (sawdust) of 150 kg/m^3, using a pressing force of 90 kN, an average final density of 1015 kg/m^3 is obtained for the briquettes.

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