RESEARCHES ON THE INFLUENCE OF MOISTURE ON THE PROCESSES OF PELLETING POWDERED BIOMASS

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The paper presents an experimentally validated mathematical model for the influence of moisture on the process of pelleting powdered biomass. The study of phenomena at the basis of the process was conducted using a heated single pellet compression device, taking into consideration a series of parameters such as raw material density and moisture and compression pressure. It was noticed that moisture as well as pressure have a great effect on the compression process, pellet density decreasing when raw material moisture increases and increasing with a higher pressure.

Keywords: biomass, pelleting, modelling, moisture.

1. Introduction

Modelling the compression process focuses on understanding the interactions between process parameters and product attributes [5]. This modeling approach helps to understand the behavior of biomass particles during granulation and to optimize process conditions in order to obtain suitable pellets. The connections between pellet density and related variables are very complicated and very nonlinear, which makes the development of a unique, general mathematical model and almost impossible.

The influence of moisture on biomass compression processes was studied for more than fifty years, as it noted in [6]. The major influence of moisture was shown in [7], [8], [9]. The influence of raw material moisture was studied both in terms of its effect on the energy consumption during the pelleting process as well as the effect on the durability of compressed products (pellets, briquettes), [13]. The hygroscopic behavior of wood pellets was studied in [10]. Moreover, authors [11] studied the existence of a moisture interval for compressed fodder, in which the avoidance of surface cracks occurs.

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Authors [12] studied alfalfa compression for moistures between 8 and 25%. Authors [14] presented results on obtaining grass pellets through extrusion at 14-16% moisture.

In [15], the authors found that a 13.3% moisture of grass leads to obtaining compressed products with the maximum cohesion. Other authors obtained optimal results in the field of biomass compression, either depending on raw material moisture, either depending on the compression force used, or on the recipe used for compression, [15], [16]. Among the advanced researches conducted at the beginning of the 20th century is situated the problem of auto humidification of the raw material to be compressed by eliminating natural binders into the process, which contribute to the cohesion of pellets, [18].

Other reference papers in this field are [11], [16], [18], [19], [20], etc.

Authors [6] review a series of studies that have varied raw material granulation, which is not performed in the present study. The situation is the same in the case of binders.

In [21], the author examines the importance of over 10 important factors influencing the compression of pharmaceutical powders, among which: moisture, compression force regime in time, die shape, granulation, lubrication, use of binders, etc.

Also, in the category of papers with results in biomass compaction, authors of paper [2] provide a dimensionally corrected empirical formula.

This paper presents the results that take into account a parameter that was not considered in our previous papers: raw material moisture.

2. Material and method

An experimentation plan was set for the compression of biomass powder. Fir tree sawdust with a 2 mm granulation was used. The experiments were conducted using a specially built single pellet pelleting device.

The following parameters were varied during experiments: die temperature, applied pressure, pelleting speed. Three values were used for the moisture of the raw material: 10%, 13% and 16%. A total number of 243 experiments were obtained for the 10 mm pelleting die [3].

The results of their statistical modelling, conducted on the basis of the most known formulas found in the specialty literature in the field, this literature being dedicated for metallic, ceramic and pharmaceutical powders, [1], modified through a dimensional method are presented in [1].

According to the elementary statistical analysis of the experimental data obtained after pelleting fir tree sawdust, raw material moisture has a great influence on raw material initial density, on pellet density, on pellet moisture, and on their length and volume.

All the parameters used during the experiments are explained in Table 1. The working method follows the one exposed in [3], but also introduces other parameters in the process, which in the formulas found in the classical literature dedicated for the processes of compressing powers, are not mentioned (are not considered or are neglected).

Table 1

Parameters of the pelleting process and of the pellets

Crt. No.	Parameter name	Notation	Unit	Physical dimension
1	Sawdust moisture	U_i	%	-
2	Die diameter	$Ø_m$	m	L
3	Die temperature	θ	ºC	
4	Maximum applied force	F_{max}	kN	MLT^{-2}
5	Piston movement speed	v	m/s	LT^{-1}
6	Consumed energy	E_c	Wh	ML^2T^{-2}
7	Pellet length	L	M	L
8	Pellet moisture	U_p	%	-
9	Pellet density	ρ_p	kg/m^3	ML^{-3}
10	Pellet volume	V_p	m^3	L^3
11	Raw material density	ρ_0	kg/m^3	ML^{-3}
12	Raw material initial value	V_0	m^3	L^3

Our research is based on Jones formula, and by adding a correction factor taking into account raw material moisture we obtained:

$$\rho_p(\rho_0, P, U) = a\rho_0 \left(\frac{P}{P_0}\right)^b U^c \quad (1)$$

where: - a, b and c are nondimensional model parameters;

- P_o is the atmospheric pressure;
- P is calculated using the force during the compression process and the geometrical characteristics of the die:

$$P = \frac{4F_{max}}{\pi Ø^2} \quad (2)$$

For obtaining the values of coefficients a, b, and c, we used the procedure of mathematical regression, the expression obtained in formula (1) was transformed logarithmically, thus resulting the following formula:

$$\ln(\rho) = \ln(a) + \ln(\rho_0) + b \cdot \ln\left(\frac{P}{P_0}\right) + c \ln(U_i) \tag{3}$$

The functional $T(a, b, c, \rho_{0i}, P_0, P_i, U_i, \rho_i)$ is formed as a sum of differences between the values calculated applying equation (3) and the real values obtained from experiments, all squared, where *i* is comprised in the interval [1, *n*] and *n* represents the number of experiments.

$$T = \sum_{i=1}^{n} \left(\ln(a) + \ln(\rho_{0i}) + b \cdot \ln\left(\frac{P_i}{P_o}\right) + c \cdot \ln(U_i) - \ln(\rho_i) \right)^2 \tag{4}$$

We note $\ln a$ with *k*.

The partial derivates are calculated:

$$\left\{ \begin{array}{l} \dfrac{\partial T}{\partial b} = 2 \sum_{i=1}^{n} \left(k + \ln(\rho_{0i}) + b \cdot \ln\left(\frac{P_i}{P_0}\right) + c \cdot \ln(U_i) - \ln(\rho_i) \right) \cdot \ln\left(\frac{P_1}{P_0}\right) = 0 \\ \dfrac{\partial T}{\partial c} = 2 \sum_{i=1}^{n} \left(k + \ln(\rho_{0i}) + b \cdot \ln\left(\frac{P_i}{P_0}\right) + c \cdot \ln(U_i) - \ln(\rho_i) \right) \cdot \ln(U_i) = 0 \\ \dfrac{\partial T}{\partial k} = 2 \sum_{i=1}^{n} \left(k + \ln(\rho_{0i}) + b \cdot \ln\left(\frac{P_i}{P_0}\right) + c \cdot \ln(U_i) - \ln(\rho_i) \right) = 0 \end{array} \right\} \tag{5}$$

In order to numerically solve the system, the constants were eliminated and the following form, that can be written as matrix multiplication was obtained:

$$\left\{ \begin{array}{c} k \sum_{i=1}^{n} \ln\left(\frac{P_i}{P_0}\right) + \sum_{i=1}^{n} \left(\ln(\rho_{0i}) \cdot \ln\left(\frac{P_i}{P_0}\right) \right) + b \sum_{i=1}^{n} \left(\ln\left(\frac{P_i}{P_0}\right) \right)^2 + c \sum_{i=1}^{n} \ln(U_i) \cdot \ln\left(\frac{P_i}{P_0}\right) = \sum_{i=1}^{n} \ln(\rho_i) \cdot \ln\left(\frac{P_i}{P_0}\right) \\ k \sum_{i=1}^{n} \ln(U_i) + \sum_{i=1}^{n} \ln(\rho_{0i}) \cdot \ln U_i + b \sum_{i=1}^{n} \ln\left(\frac{P_i}{P_0}\right) \cdot \ln(U_i) + c \sum_{i=0}^{n} (\ln(U_i))^2 = \sum_{i=1}^{n} \ln(\rho_i) \cdot \ln(U_i) \\ k \sum_{i=1}^{n} 1 + \sum_{i=1}^{n} \ln(\rho_{0i}) + b \sum_{i=1}^{n} \ln\left(\frac{P_i}{P_0}\right) + c \sum_{i=1}^{n} \ln(U_i) = \sum_{i=0}^{n} \ln(\rho_i) \end{array} \right\} \tag{6}$$

$\leftrightarrow$ A · C = B

where:

$$A = \begin{bmatrix} \sum_{i=1}^{n}\left(\ln\left(\frac{P_i}{P_0}\right)\right)^2 & \sum_{i=0}^{n}\left(\ln(U_i)\ln\left(\frac{P_i}{P_0}\right)\right) & \sum_{i=0}^{n}\left(\ln\left(\frac{P_i}{P_0}\right)\right) \\ \sum_{i=1}^{n}\left(\ln U_i \ln\left(\frac{U_i}{P_0}\right)\right) & \sum_{i=0}^{n}[\ln(U_i)^2] & \sum_{i=0}^{n}(\ln(U_i)) \\ \sum_{i=1}^{n}\left(\ln\left(\frac{P_i}{P_0}\right)\right) & \sum_{i=0}^{n}(\ln(U_i)) & \sum_{i=0}^{n}1 \end{bmatrix} \tag{7}$$

$$B = \begin{bmatrix} \sum_{i=1}^{n}\left[\ln\left(\frac{\rho_i}{\rho_0}\right)\cdot\left(\ln\left(\frac{P_i}{P_0}\right)\right)\right] \\ \sum_{i=1}^{n}\left(\ln\left(\frac{\rho_i}{\rho_0}\right)\cdot\ln(U_i)\right) \\ \sum_{i=1}^{n}\left(\left(\frac{\rho_i}{\rho_0}\right)\right) \end{bmatrix} \tag{8}$$

$$C = \begin{pmatrix} b \\ c \\ k \end{pmatrix} \tag{9}$$

In order to measure the error between the calculated and the experimental data, we used two norms:

$$\varepsilon_g = \frac{\sqrt{\sum_{i=1}^{n}\left(\rho_{p\ exp\ i} - \rho_p(\rho_{0\ \mathrm{exp}\ i}, P_i)\right)^2}}{n \cdot \overline{\rho_{p\ exp}}} \tag{10}$$

and

$$\varepsilon_{max} = \frac{\max_{i=1,\dots,n}\left|\rho_{p\ exp\ i} - \rho_p(\rho_{0\ \mathrm{exp}\ i}, P_i)\right|}{\overline{\rho_{p\ exp}}} \tag{11}$$

where ε_g is the global error, ε_{max} is the maximum error, $\rho_{p\ exp\ i}$ is the value of the pellet obtained during experiments with the order index i, $\rho_p(\rho_{0\ \mathrm{exp}\ i}, P_i)$ is the theoretical value of pellet density resulted in experiments with the order index i,

$\overline{\rho_{p\ exp}}$ is the average value of experimental densities string, and n is the number of experiments.

3. Results

After conducting the experimental researches, a series of results were obtained for the 243 pellet samples produced during the experimental researches, which are synthetically presented in table 2.

Table 2

Results obtained after the experimental researches

Sample	Raw material density ρ_0 [kg/m^3]	Initial moisture U_i [%]	Granulation g [m]	Temperature θ [ºC]	Pelleting speed v [m/s]	Maximum force F_{max} [kN]	Pellet density ρ_p [kg/m^3]	Pellet moisture U_p [%]
1	136.08	10	0.002	70	0.0021	10	982.81	8.94
2	136.08	10	0.002	70	0.0021	10	972.19	8.72
3	136.08	10	0.002	70	0.0021	10	983.44	9.01
4	136.08	10	0.002	80	0.0021	10	985.66	8.84
5	136.08	10	0.002	80	0.0021	10	979.67	8.52
…	…	…	…	…	…	…	…	…
239	147.37	16	0.002	80	0.0028	30	845.63	13.51
240	147.37	16	0.002	80	0.0028	30	830.48	12.85
241	147.37	16	0.002	90	0.0028	30	778.50	12.35
242	147.37	16	0.002	90	0.0028	30	797.78	12.42
243	147.37	16	0.002	90	0.028	30	801.75	12.51

By applying the least squares method for all 243 experiments, relative to the parameters involved in formula (1), the values of model parameters are obtained:

$$a = 17.698, b = 0.081, c = -0.61 \qquad (12)$$

By replacing the values of model parameters in formula (1), we obtain:

$$\rho_p(\rho_0, P, U_i) = 17.698\rho_0 \left(\frac{P}{P_0}\right)^{0.081} U_i^{-0.61} \qquad (13)$$

A graphical comparison between the experimental and the calculated data is shown in Figure 1.

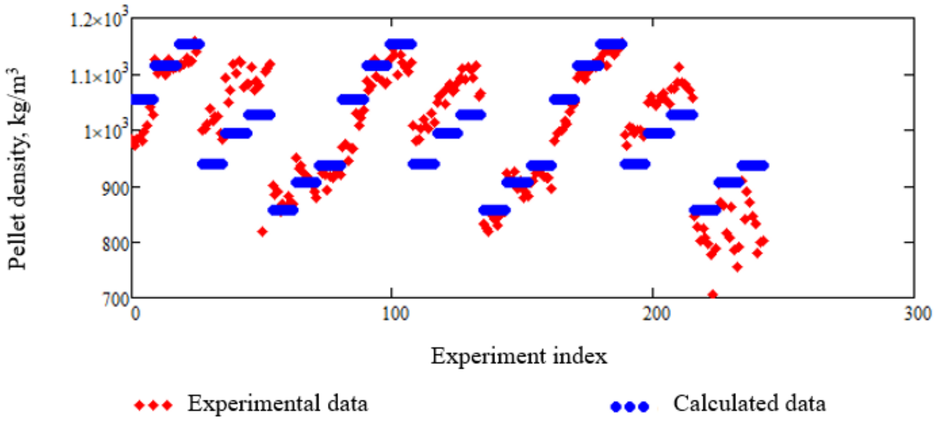

Fig. 1. Comparative graphical representation between the experimental data and the data calculated using formula (1), with values (3) of model parameters

As it can be noticed in (1), Jones type formula searches a relation connecting the relative density to the relative pressure, both maximums of the compression process but, in addition to [3], on raw material (fir tree sawdust) moisture. In order to estimate the expectancies on the interpolation precision, it is useful to estimate the correlation between the two quantities. For the experimental data obtained for the 10 mm orifice die, Pearson correlation between relative density and relative pressure has the value 0.271.

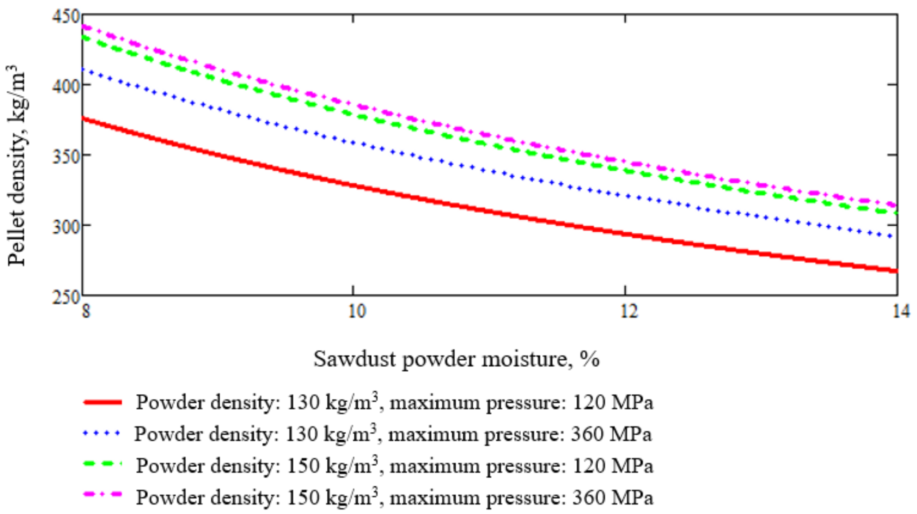

Fig. 2. Dependency of pellet density on the moisture of sawdust used as raw material, for fixed values of raw material density and maximum compaction pressures

The graphical representation of the dependency of pellet density on sawdust density and on the maximum pressure applied by the compression installation, is given in Figure 3.

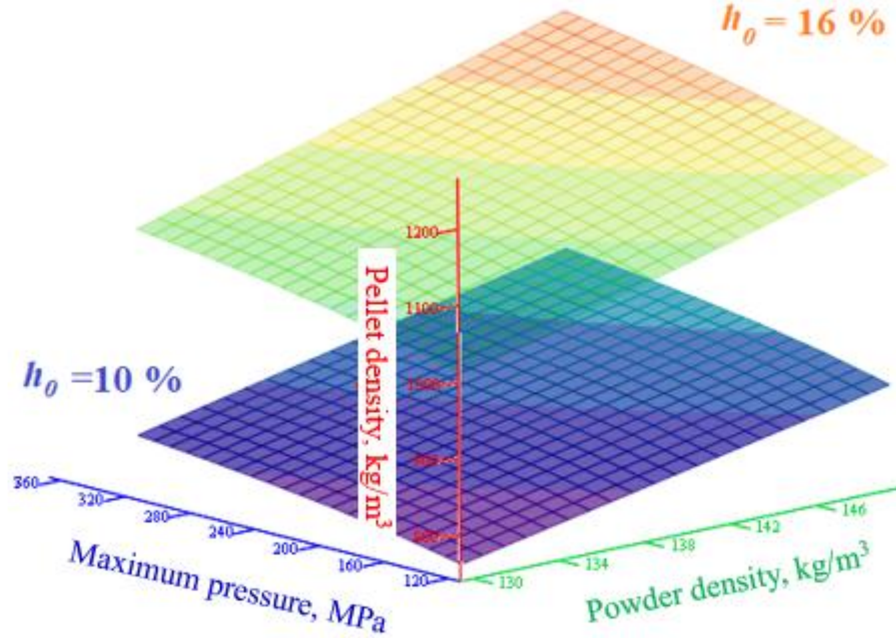

Fig. 3. Pellet density dependency on sawdust density and on maximum pressure reached in the installation, for the limits of the moisture interval considered for experiments

Figure 3 is a representation in surface and isocline form, of the dependency of pellet density on two variables (according to (1)), the initial density of pellets and the maximum pressure reached in the compression installation.

The precision estimators were calculated for the dependency law determined though the method described in the previous chapter, obtaining the following results: e_g = 0.003742 and e_{max} = 0.20746756.

4. Conclusions

The dependency law presented in this paper and calibrated on the experimental data, is linear in terms of raw material density. Therefore, pellet density depends linearly on the density and the volume of raw material introduced in the pelleting process. The dependency of pellet density is nonlinear in relation to the relative pressure and therefore to the maximum force of pressing the material thorough the die orifices.

The formula for the dependency of pellet density on the process parameters, show that:

- pellet density increases (nonlinearly) with the maximum pelleting force (implicitly with the maximum force reached). For the maximum force applied of 10 kN, pellet density varied between 706.25 and 1049.3 kg/m^3, for 20 kN between 754.69 and 1126.89 kg/m^3 and for 30 kN between 778.50 and 1160.22 kg/m^3.
- pellet density decreases nonlinearly when increasing the moisture of the raw material introduced in the pelleting process. For the 10% raw material moisture we obtained densities between 945.75 and 1160.22 kg/m^3, for 13% between 818.70 and 1123.16 kg/m^3 and for 16% between 706.25 and 949.27 kg/m^3.

The results and conclusions presented in this paper refer strictly to the multidimensional parametric interval considered in the experiments. Also, the dependency of some quality parameters of the pelleting process on some parameters that were neglected or not considered in experiments (raw material granulation, die diameter) can influence and even change to some extent the results presented in this paper.

The dependency of pellet density on the process parameters considered does not show any interesting critical points. The only extremal points are found on the frontiers of the definition domain considered experimentally.

The attempts for statistical modelling presented in this paper represent only a small part of the possible ones. Many more, with superior properties compared to those already tested, can emerge during more complex (theoretical, but more important experimental) studies.

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