RESEARCHES ON THE STATISTICAL MODELLING OF THE PROCESSES OF PELLETING BIOMASS, TESTING CLASSIC POWDER COMPACTION MODELS

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CERCETĂRI PRIVIND MODELAREA STATISTICA A PROCESELOR DE PELETIZARE A BIOMASEI, TESTAREA MODELELOR CLASICE ALE COMPACTARII PULBERILOR

Găgeanu I.*$^{1)}$, Cârdei P.$^{1)}$, Matache M.$^{1)}$, Voicu Gh.$^{2)}$ [1]
$^{1)}$ National Institute of Research – Development for Machines and Installations Designed
to Agriculture and Food Industry- INMA Bucharest / Romania; $^{2)}$ University Politehnica of Bucharest / Romania
E-mail: iulia.gageanu@gmail.com
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ABSTRACT

The paper presents the main performances of formulas used in the literature in the field of compacting metallic, ceramic and pharmaceutical powders, in the case of applying them to biomass powders (fir tree sawdust). Because the authors have modified classic formulas in this field, the research of statistic modelling of the powder compaction process, it was normal to begin with functions of the same type as those presented in this paper. The performance of these formulas will constitute a comparison basis for any possible new formulas proposed. Through the modifications brought to formulas in the classic literature, formulas used in this material have an originality character and are subjected to validation for biomass powders in this paper.

REZUMAT

Articolul prezintă principalele performanțe ale formulelor folosite în literatura de specialitate în domeniul compactării pulberilor metalice, ceramice şi farmaceutice, în cazul aplicării puberilor din biomasă (rumeguş de brad). Deoarece autorii au modificat formulele clasice din acest domeniu, cercetarea modelării statistice a procesului de compactare a pulberilor, era normal să fie început cu funcții de tipul celor expuse în acest articol. Performanțele acestor formule vor constitui o bază de comparație pentru eventualele formule noi propuse. Prin modificările efectuate formulelor din literatura clasică, formulele folosite în acest material au un caracter de originalitate şi sunt supuse în acest articol validării pentru pulberi de biomasă.

INTRODUCTION

Powder compaction processes, thus obtaining tablets, have been already used for a considerable and even very long period of time compared to human lifetime. It is estimated, that the sintering of ceramic powders can be considered as being 26000 years old (*German R.M., 2013*). Also, it is considered that the science of sintering emerged in 1940 and matured beginning with the 80's. (*German R.M., 2016)*. Among the first powders processed through compaction we find ceramic and metallic powders. The first papers on obtaining medical tablets through compaction have begun to appear after 1940, (*Celik M., 2016*). Plastic powders are also processed through cold or thermally controlled compaction processes. Composite materials are in some cases obtained by mixing and compacting metallic, ceramic, plastic or other types of powders.

Coal was also subjected to this type of manufacturing process, (*Nadon G.C., 1998*), thus obtaining briquettes, blocks, etc. Biomass also started to be compressed and prepared in compact units, easier to be handled and used for feeding animals, obtaining biofuels, useful chemical compounds, etc. In India, manure cakes are also used from time immemorial. The first commercial production factory opened in 1982, producing almost 900 metric tons of biomass. In 1984, improvements were brought, building factories that improved the efficiency and quality of briquettes (using among others rice husk and molasses) (*https://en.wikipedia.org/wiki/Biomass_briquettes*).

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[1] *Găgeanu I., Ph.D. Stud. Eng.; Cârdei P., Math.; Matache M., Ph.D. Eng.; Voicu Gh., Prof. Ph.D. Eng.*

Densification or compaction of biomass thus forming pellets or briquettes is an essential process for the production of biofuels. The particles of grinded biomass behave differently under the action of the different applied forces. Thus, it is important to investigate changes in the density and volume of the compacted material with the application of pressures. (*Adapa et al., 2009; Comoglu, 2007; Tabil et al., 2011*).

Taking into consideration the development of this processing procedure in the field of biomass, it was natural to have a large quantity of papers dedicated to the mathematical modelling of this process.

The literature provides a series of simple mathematical models, listed and reconsidered in (*Cardei and Gageanu, 2017*), which can be tested in the purpose of mathematically modelling the studied process. Generally, the models in (*Cardei and Gageanu, 2017*) limit themselves to considering initial and final density and volume parameters and the pressure (force) control parameter. If these models are satisfactory from the point of view of precision, they can be further extended with additional parameters considered for the process of compacting powders in our experiments [8]. Such models are not new. After 1950, more and more complex models began to appear in the literature, containing more parameters for the process of compacting powders or grinded materials.

A series of models for biomass, which were not examined in (*Cardei and Gageanu, 2017*), are given in (*Mani et al, 2003*). There, researches beginning from the 60's on the influence of temperature, moisture, additives, granulation, etc. are highlighted. A comprehensive list of parameters for the process of compressing biomass, and of the main laws of the compression process, are given in (*Shaw M, 2008*). (*Voicea et al, 2016*) propose a formula for the phenomenon of compacting biomass, also covered in this paper, where compression force appears instead of pressure, as well as other parameters, the formula having dimensional substantiation.

MATERIALS AND METHODS

The first attempts for mathematical modelling that we tested are based on calculation formulas describing the process of compacting powders found in the literature synthetized in paper (*Cardei and Gageanu, 2017*). Due to the fact that among the parameters taken into account for the processes of compacting metallic, ceramic or pharmaceutical powders, only the relative density and pressure are found in (*Cardei and Gageanu, 2017*) and also in the experiments conducted in (*Mani et al, 2003*), this paper will only evaluate the assessment precision of formulas including these parameters.

In the purpose of evaluating the modelling capacity of formulas in (*Cardei and Gageanu, 2017*), for the process of pelleting fir tree sawdust, original versions proposed by the authors were used for these formulas, by dimensionally correcting the initial versions of formulas considered in (*Cardei and Gageanu, 2017*).

For each formula with potential of modelling the experimental process of pelleting fir tree sawdust, the model parameters are determined using the least squares method applied on the set of 243 data groups recorded for the 10 mm diameter die. The same thing can be done for the 8 mm diameter die. Two versions are considered for the approximation precision estimators and the models are compared through the means of their values.

In table 1, we present the parameters involved in the experimental process. The same table presents the measurement units and the physical dimension.

Table 1

Parameters of the pelleting process and of the pellets obtained

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
13	Raw material granulation	g	m	L

Jones formula

The first formula investigated is Jones formula:

$$\rho_p(\rho_0, P) = \rho_0 e^b \left(\frac{P}{P_0}\right)^m \tag{1}$$

where b and m dimensionless model parameters, e is defined by the limit:

$$e = \lim_{n\to\infty}\left(1+\frac{1}{n}\right)^n \tag{2}$$

P_0 is the atmospheric pressure:

$$P = \frac{4F_{max}}{\pi \emptyset^2} \tag{3}$$

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:

$$b = 1.321, m = 0.081 \tag{4}$$

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

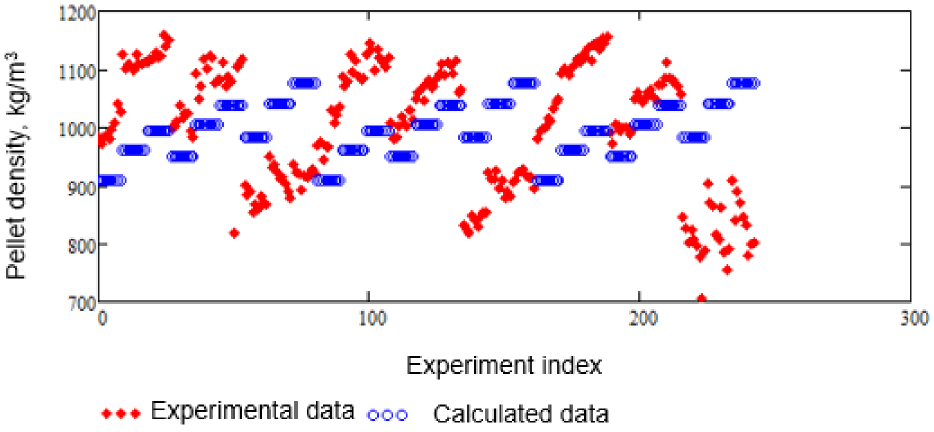

Fig. 1 - Comparative graphical representation of the experimental data and the data calculated using formula (1), with values (4) of model parameters

To measure the error of the data calculated compared to the experimental data, two norms were used:

$$\varepsilon_g = \frac{\sqrt{\sum_{i=1}^{n}\left(\rho_{p\ exp\ i} - \rho_p(\rho_{0\ \mathrm{exp}\ i}, P_i)\right)^2}}{n \cdot \overline{\rho_{p\ exp}}} \tag{5}$$

and

$$\varepsilon_{max} = \frac{\max\limits_{i=1,\dots,n}\left|\rho_{p\ exp\ i} - \rho_p(\rho_{0\ \mathrm{exp}\ i}, P_i)\right|}{\overline{\rho_{p\ exp}}} \tag{6}$$

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 the experiment with the order index i, $\rho_p(\rho_{0\ \mathrm{exp}\ i}, P_i)$ is the theoretical value of the density of the pellet resulted in the experiment with the order index i, $\overline{\rho_{p\ exp}}$, is the average value of the string of experimental pellet densities, and n is the number of experiments.

As seen in Eq.1, Jones formula seeks a relation connecting the relative density to the relative pressure, both maximums of the compression process. In order to estimate the expectations on the interpolation precision, it is useful to estimate the correlation between the two quantities. For the experimental data obtained for the 10 mm diameter die, Pearson correlation between the relative density and the relative pressure has the value of 0.271.

The graphical representation of the dependency of pellet density to the sawdust density and maximum pressure applied by the pelleting installation is given in figure 2 and 3. Figure 2 gives the graphical representation of pellet density as partial functions of raw material density for two values of the maximum pressure applied. Figure 4 represents, in the form of surface and isocline, the dependency of pellet density on two variables (according to formula (1)), the initial pellet density and the maximum applied pressure in the pelleting installation.

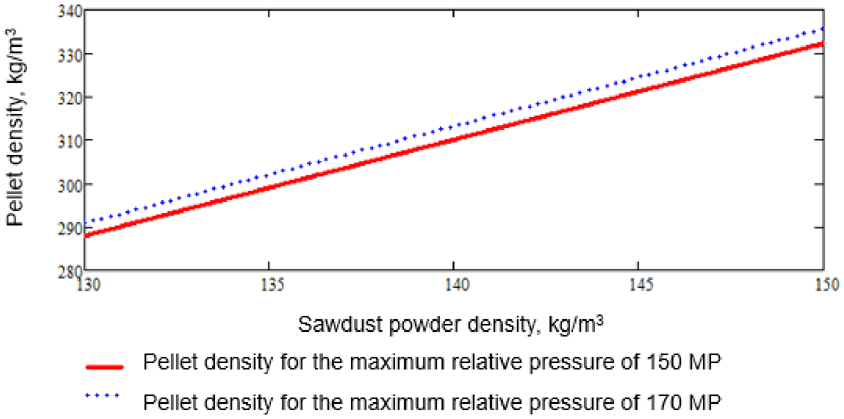

Fig. 2 - The dependency of pellet density on the density of sawdust used as raw material

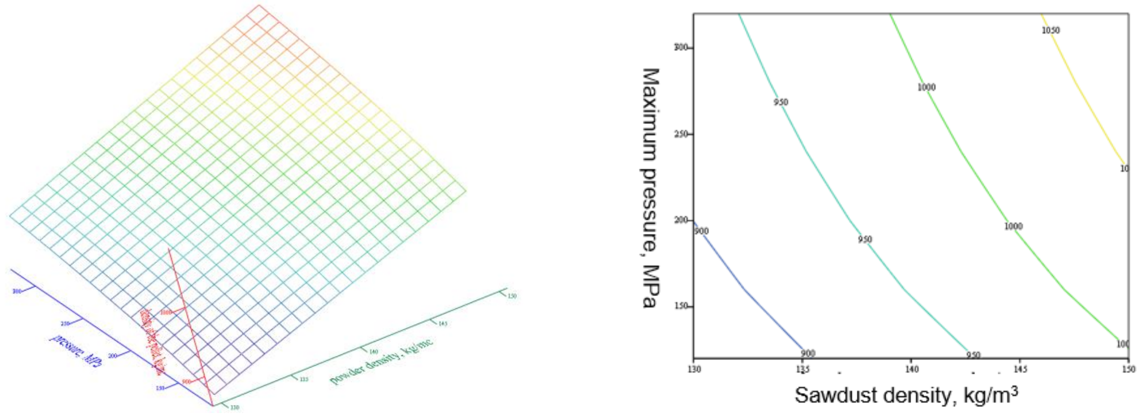

Fig. 3 - The dependency of pellet density on the sawdust density and on the maximum pressure applied

RESULTS

According to the method given in the previous chapter, other laws were tested, describing the dependency between the relative density (the ratio between pellet density at the finish of the pelleting process and the density of the powder introduced in the process) and relative pressure (the ratio between the maximum pressure of the piston and the atmosphere pressure) or between the relative volume (the ratio between pellet volume after compression and the initial volume of the powder raw material) and the relative pressure.

Heckle model has the form:

$$\rho_p(\rho_0, P) = \frac{\rho_0}{1 - e^{0.00000552\frac{P}{P_0} - 0.17}} \tag{7}$$

Panelli-Filho model:

$$\rho_p(\rho_0, P) = \rho_0 \cdot \left(1 + e^{0.003913\sqrt{\frac{P-P_0}{P_0}} + 1.598}\right) \tag{8}$$

Ge model:

$$\rho_p(\rho_0, P) = \frac{\rho_0}{1 - e^{-10^{-0.518}\left(\frac{P}{P_0}\right)^{-0.087}}} \tag{9}$$

Shapiro Kopopicki model:

$$\rho_p(\rho_0, P) = \rho_0 \cdot e^{1.958 - 0.0001453\sqrt{\frac{P-P_0}{P_0}} - 0.000001531\frac{P-P_0}{P_0}} \tag{10}$$

Gurnham model:

$$\rho_p(\rho_0, P) = \rho_0 \cdot \left(0.583 \cdot \ln\left(\frac{P}{P_0}\right) + 2.553\right) \tag{11}$$

Walker model:

$$V_p(V_0, P) = V_0 \cdot e^{-1.321} \cdot \left(\frac{P}{P_0}\right)^{-0.081} \tag{12}$$

Kawakita-Lude model:

$$V_p(V_0, P) = V_0 \cdot \left(1 - \frac{0.039(P - P_0)}{P_0 + 0.045 \cdot (P - P_0)}\right) \tag{13}$$

Smith model:

$$V_p(V_0, P) = \frac{V_0}{1 + 0.119 \cdot \left(\frac{P}{P_0}\right)^{\frac{1}{2}}} \tag{14}$$

Mewes model (for straw compaction): the model is the first of the three given by (*German, 2013*) and after processing and taking into account the dimensionless requirement of the arguments of transcendent functions, we obtain:

$$\rho_p(\rho_0, P) = \rho_0 \left(290.133 \cdot \frac{P}{P_0}\right)^{1.13} \tag{15}$$

Faborode – O'Callaghan formula, elaborated for straw compaction, is explicit in compaction pressure and, for the experiments to which this paper refers, the following concrete formula is obtained:

$$P(\rho_0, \rho) = 8712.225871 \cdot P_0 \cdot \frac{\rho_0}{\rho} \cdot \exp\left(0.281488 \cdot \left(\frac{\rho}{\rho_0} - 1\right) - 1\right) \tag{16}$$

Ferrero model, takes, using the experimental results from this paper, the concrete form in formula (17):

$$\rho_p(\rho_0, P) = \rho_0 \cdot \left[1 + \left(5.996517 + 0.000087 \frac{P}{P_0}\right) \cdot \left(1 - \exp\left(-0.002117 \frac{P}{P_0}\right)\right]\right. \tag{17}$$

Viswanathan-Gothandapani model, leads, for the experimental data used in this paper, to relation (18):

$$P(\rho_0, \rho) = P_0 \cdot \left[18286.179625 - 4981.649819 \cdot \left(\frac{\rho}{\rho_0}\right) + 383.046581 \cdot \left(\frac{\rho}{\rho_0}\right)^2\right] \tag{18}$$

Cardei-Voicea model, is a simplified version of the model in paper (*Voicea et al., 2016*) and leads, for the experimental data used in this paper, to relation (19):

$$\rho_p(\rho_0, F_{max}, v, U_i) = \rho_0 \left(\frac{F_{max} + F_0}{F_0}\right)^{0.225} \cdot \left(\frac{v + v_0}{v_0}\right)^{-0.0008844} \cdot U_i^{-0.449} \tag{19}$$

where F_0 =0.02 N (the product of raw material mass per pellet and the gravitational acceleration), $v_0 = 0.0013$ m/s (the minimal value of the piston's forwarding speed).

Table 2 presents the precision estimators for the dependency laws determined through the method described in the previous chapter. It is noted that the values of precision estimators are similar for many of the formulas proposed and objectified for the experimental data obtained for compacting fir tree sawdust.

Table 2

Precision estimators of dependence laws taken from the literature dedicated to the compaction of metallic, pharmaceutical and ceramic powders

Law	ε_g	ε_{max}
Jones	0.008229	0.29711636
Heckel	0.008295	0.28733083
Panelli-Filho	0.008244	0.29698397
Ge	0.008230	0.29625440
Shapiro-Kopopicki	0.008613	0.33068074
Gurnham	0.008241	0.30700960
Walker	0.008715	0.39496253
Kawakita-Ludde	0.008767	0.38793788
Smith	0.014000	0.46457425
Mewes-1	0.010000	0.43145241
Faborode-O'Callaghan	0.025000	0.70467121
Ferrero	0.008227	0.30515891
Viswanathan-Gothandapani	0.024000	0.76075107
Cardei-Voicea	0.005742	0.28148792

In a similar manner, each of the models (7) – (19) can be completed with graphical representations made for model (1) in figures 1-3.

CONCLUSIONS

All the dependency laws taken into consideration, calibrated on the experimental data obtained are linear in the density of the raw material and in its volume. Therefore, the density and volume of pellets depend linearly on the density and volume of the raw material introduced in the process. The dependency of pellet density and volume is nonlinear in relation to the relative pressure and, therefore with the maximum force of pressing the material in the die.

Pellets density function increases monotonously with the density of the raw material and with the maximum pressing force and does not show interesting critical points. The only extremal points are found on the frontiers of the definition domain considered experimentally.

Out of the formulas tested, the best global precision as well as the one given by the maximum error is obtained for Cardei-Voicea formula. This formula can still be improved, taking into account the granulation and temperature. In this paper, only formula (20) considers the very important factor represented by raw material moisture. It is possible for formulas (1) – (19) to obtain precision performances even better than (20) if, in each of them, the factor dependent on moisture is considered. We remind that the powder compression models (1)-(19), presented in this paper, are not those initially proposed by their original authors, but are modified to meet the dimensionless criterion of transcendent function arguments.

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REFERENCES

[1] Adapa P. K., L. G. Tabil, and G. Schoenau, (2009), Compression Characteristics of Selected Ground Agricultural Biomass Agricultural Engineering International: *CIGR E-journal*, Manuscript 1347, Vol. 11;

[2] Cardei P., Gageanu I., (2017), A Critical Analysis of Empirical Formulas Describing the Phenomenon of Compaction of The Powders, *J. Modern Technology & Engineering*, vol. 2, No. 1, pp. 1-20;

[3] Celik M., (2016), Pharmaceutical Powder Compaction Technology, Drugs and Pharmaceutical Sciences, vol. 197, ISBN-13: 978-1420089172;

[4] Çomoğlu T., (2007), An Overview of Compaction Equations, *Journal of the Faculty of Pharmacy*. 36(2), pp.123-133, Ankara / Turquie;

[5] Gageanu I., Cardei P., Matache M., Voicu Gh., (2019), Description of the experimental data of the pelleting process using elementary statistics, *Proceedings of the Sixth International Conference “Research People and Actual Tasks on Multidisciplinary Sciences*”, C, pp. 436-444, Lozenec / Bulgaria;

[6] German R.M., (2013), History of sintering: empirical phase, Powder Metallurgy, vol. 56, issue 2, pp. 117-123, https://www.tandfonline.com/doi/abs/10.1179/1743290112Y.0000000025;

[7] Mani S., Tabil L.G., Sokhansanj S., (2003), An Overview of Compaction of Biomass Grinds, *Powder handling & processing*, vol. 15, no.2, pp. 1-9;

[8] Nadon G.C., (1998), Magnitude and timing of peat-to-coal compaction, *Geology*, vol.26(8): pp.727-730;

[9] Shaw M., (2008), *Feedstock and process variables influencing biomass densification*, Thesis for Degree of Master in Science, Department of Agricultural and Bioresource Engineering University of Saskatchewan Saskatoon, Saskatchewan;

[10] Tabil L.G.,Adapa P, Kashaninejad M., (2011), Biomass Feedstock Pre-Processing. Part 2: Densification, *Biofuels Engineering Process Technology*, pp. 440-464;

[11] Voicea I., Voicu Gh., Cardei P., Vladut V., Gageanu I., Daraban A., (2016), Theoretical and experimental research on the process of biomass briquetting, *U.P.B. Scientific Bulletin*., Series D, Vol. 78, Issue 3; pp. 203-214;

[12] *https://en.wikipedia.org/wiki/Biomass_briquettes.*