RESEARCH ON THE VALIDATION OF MATHEMATICAL MODELS FOR BIOMASS POWDER COMPACTION USING A RING DIE PELLETING EQUIPMENT
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CERCETĂRI PRIVIND VALIDAREA MODELELOR MATEMATICE PENTRU COMPACTAREA PULBERILOR DE BIOMASĂ UTILIZÂND UN ECHIPAMENT DE PELETIZARE CU MATRIȚĂ INELARĂ

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ABSTRACT
The paper presents the experimental validation of two mathematical models describing biomass powders compaction (a model that expresses the final density of pellets as determined by the final pressure applied during the process, the initial material moisture and the initial density of the material, but also a mathematical model obtained through dimensional analysis, using Π theorem, expressing the density of pellets as determined by pressure, heat, the initial density of the material, the pelleting speed of and the initial volume of the material), through experimental researches using a ring die pelleting equipment. The results showed a strong correlation between the data estimated theoretically and the experimental data, but also a strong influence of biomass material initial moisture on the density of the pellets obtained.

REZUMAT
Articolul prezintă validarea experimentală a două modele matematice care descriu compactarea pulberilor de biomasă, (un model matematic ce exprimă densitatea finală a peletelor ca fiind determinată de către presiunea finală aplicată în timpul procesului, umiditatea inițială a materialului și densitatea inițială a materialului, dar și un model matematic obținut prin analiză dimensională, utilizând teorema Π, care exprimă densitatea peletelor ca fiind determinată de presiune, căldură, densitatea inițială a materialului, viteza de peletizare și volumul inițial al materialului), prin cercetări experimentale pe un echipament de peletizat cu matriță inelară. Rezultatele au arătat o corelare foarte bună a datelor estimate teoretic cu cele experimentale, dar și o puternică influentă a umidității inițiale a materialului din biomasă asupra densității peletelor obținute.

INTRODUCTION
Currently, researches in the field of obtaining solid biofuels is a major concern in the field of mechanical engineering, whose main aim is to optimize the densification processes, improve the quality of biomass products, minimize costs, increase the yields of compression equipment, as well as contribute to the protection of the environment (*Anukam et al., 2021; Gilvari et al., 2021, Golub et al., 2020*).

In order to obtain solid biofuels with adequate density and durability, there must be a very good correlation between the physical-chemical properties of the biomass used as raw material (particle size, material moisture) and the characteristics of the pelleting equipment (type of die, size of orifices, type of material drive, pelleting speed, etc.). Pellets can be formed by compacting particles by force using pressure, when the particles join together with or without the use of binders (*Celik, 2016; Lisowski et al., 2020; Serrano et al., 2011*).

Agricultural and lignocellulosic biomass compaction or densification in the form of pellets is an essential process for obtaining biofuels. It was found by various researchers that grinded biomass particles behave in a different manner when various forces are applied (*Agar et al., 2018; Andreiko and Grochowicz, 2007).* Therefore, it is important to investigate the changes in the density and volume of the material when applying pressure. Theoretical and experimental researches in the field of biomass pelleting aim to increase the quality of the finished products, correlated with the decrease of the costs and the impact on the environment (*Garcia-Maraver et al., 2015; Lisowski et al., 2019; Welker et al., 2015*).

It was found (*Ndiema et al., 2002*) that by applying high pressures and temperatures during densification, solid bridges can develop by diffusing molecules from one particle to another at points of contact, thus increasing the density.

Related to the influence of biomass on the pelleting process, researchers (*Frodeson et al., 2019*) have found that pellets have poor quality in terms of both density and durability when using biomass with a very low initial moisture (2%, 4 %) but also in the case of high initial moisture (14 %, 16%). Demirbas A. and Dermibas A.S. (*Demirbas and Dermibas, 2004*) found that by increasing the moisture content from 7 to 15% in spruce sawdust, the durability of compressed biomass increased significantly. Mani, Tabil and Sokhansanj (*Mani et al. 2006*), in their paper on the densification of corn stalks, found that low material moisture (5-10%) led to more stable, denser, but also more durable briquettes.

Studying the effect compaction force on pellet density, using forces of 6kN, 12 kN, 16 kN and 20 kN, authors of paper (*Poddar et al., 2014*) determined that pellet density gradually increased for samples obtained increasing compaction force.

One of the most important reasons for putting the experimental data into a compression model (equation) is to generate diagrams that make their comparison easier. Compression models help show the behaviour of powder biomass particles during the compression (pelleting) process and can help optimize the parameters needed to obtain good quality pellet (*Comoglu, T., 2007*).

In order to be able to determine the influence of the disturbing factors on the pelleting process, which ultimately lead to decreases in the quality of the obtained products or even to the blocking of the equipment, a series of experimental determinations must be made with the variation of these disturbing factors.

The paper presents the validation of two mathematical models for the densification of powder biomass with experimental data obtained using ring die pelleting equipment.

MATERIALS AND METHODS

Taking into account the parameters that have influence on the pelleting process (Table 1) on ring die pelleting equipment, two mathematical models are proposed to express the density of pellets.

Table 1

Parameters of the pelleting process taken into account in the analysis

Parameter	Name	Notation	Measurement unit	Physical dimension
1	Quantity of heat	Q	kg m^2/s^2	ML^{2}T^{-2}
2	Compression pressure	p	N/m^2	ML^{-1}T^{-2}
3	Initial material moisture	U_i	%	-
4	Pellet density	ρ_p	kg/m^3	ML^{-3}
6	Volumetric mass of raw material	ρ_0	kg/m^3	ML^{-3}
7	Initial volume of the raw material	V_0	m^3	L^3
8	Pelleting speed	v	m/s	LT^{-1}

The first model used for experimental validation is based on the determination of pellet density as a function of the pressure applied to the biomass, but takes into account the correction factor that takes into consideration the moisture of the raw material.

The proposed formula is presented in relation (1).

$$\rho_p(\rho_0, p, U_i) = a \times \rho_0 \left(\frac{p}{p_0}\right)^b \times U_i^c \tag{1}$$

where: a, b and c are model parameters, [dimensionless];

p_0 is the atmospheric pressure, [MPa];

p - compression pressure, [kPa];

$$p = \frac{4F_{max}}{\pi d^2} \tag{2}$$

F_{max} – force applied to the raw material, [kN];

d - diameter of the die, [m].

The second model represents a more complex version, taking into account both the moisture of the raw material and the temperature of the die during the pelleting process, and it was obtained using the Buckingham theory (*Buckingham, 1914*). The model obtained is given in formula (3):

$$\rho_p(\rho_0, p, U_i)=\rho_0\left(\frac{Q}{\rho_0 \cdot v^2 \cdot V_0}\right)^a\left(\frac{p}{p_0}\right)^b \times U_i^c. \tag{3}$$

In the model in relation (3), the control parameter represented by the temperature of the die was introduced in a dimensionless factor considering the temperature as having an energetic nature (quantity of heat), in the second factor of the right member, which rises to the power of a.

In order to validate the proposed mathematical models, experimental tests were conducted for pelletizing fir sawdust using a pelletizing press with a fixed ring (cylindrical) die with 8 mm pelleting orifices and two pressing rollers (fig. 1), in which biomass was introduced at the top, the actual pelleting process being performed at the point of contact between the pressing rollers and the die.

The pelleting equipment with fixed ring die (having compression orifices with a diameter of 8 mm) and press rollers driven by a rotor shaft is an equipment designed to obtain pellets that can be used in installations for the production of heat and domestic hot water, for small and medium-sized farms, as well as for households, with the aim of ensuring energy independence.

The mass of material (sawdust) from grinded solid biomass is introduced into the hopper of the equipment, from there being transported inside the press by an auger. The pellets are discharged at the bottom of the equipment, just below the die.

Fig. 1 - Ring die pelleting equipment used for experiments

1. material hopper; 2. pellet cutting blade motor; pelleting equipment casing;
4. feed hopper motor; 5. control panel; 6. pelleting equipment main motor

The material used for experiments was represented by fir tree sawdust. To ensure an even distribution of particles, the sawdust was sieved using a Retsch AS 200 sieving equipment, and only sawdust with sizes smaller than 2 mm was used.

Using the pelleting equipment, the pellets from fir sawdust were obtained using the following methodology:

1. The initial moisture of the raw material was determined using the thermal balance.

2. The required quantity (10 kg for each sample) to be introduced into the pelleting equipment was measured using a balance.

3. The pellet casing and blade for cutting the pellets were demounted to allow the force measurement dose to be mounted on the ring die and a material feed funnel was fitted;

4. The force gauge was mounted on the cylindrical die in order to measure the compressive force and then to calculate the pelletizing pressure by reference to the diameter of the die.

5. the dose was connected to a data acquisition system (MGCPlus – HBM, Germany), that in turn was connected to a computer in order to record the data;

6. The actual pelleting process was conducted using the pelleting equipment;

7. The size of 40 pellets in each pellet sample was measured.

8. Those 40 pellets from each sample were weighed for further determination of density.

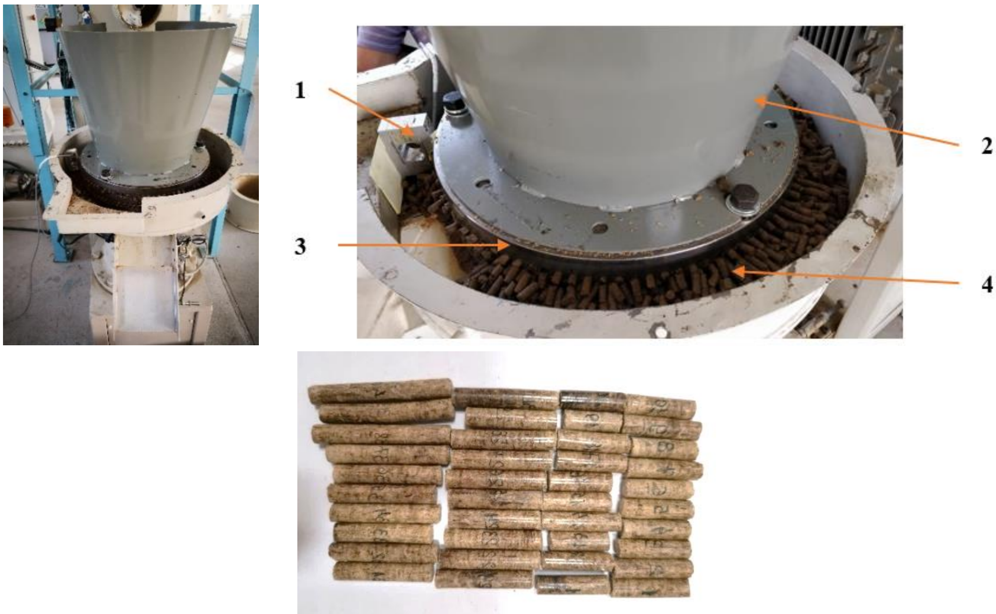

Fig. 2 - Aspects during the experiments using the ring die equipment
1. force gauge; 2. material feed funnel; 3. pelleting die; 4. Pellets

A number of 6 samples (2 samples for the three raw material moistures used: 10%, 13% and 16%) were obtained from fir tree sawdust. The three moistures were obtained by either drying the biomass sawdust in the oven or watering and thoroughly mixing the material.

RESULTS

During the experiments, the following compression pressures were recorded: 107 MPa for experiments conducted using biomass material with 10% and 13% initial moisture and 105 MPa for experiments conducted using material with 16% initial moisture.

Following the experimental researches on the pelleting equipment with fixed ring die and the measurements and density calculations, the following results were obtained, presented in tables 2 - 4.

Table 2

Results obtained after conducting the experimental researches for the initial moisture of 10%

Sample	ρ_p kg/m³	Sample	ρ_p kg/m³	Sample	ρ_p kg/m³	Sample	ρ_p kg/m³
1	1074.38	**11**	1145.12	**21**	1178.37	**31**	1152.13
2	1123.98	**12**	1121.47	**22**	1147.93	**32**	1198.78
3	1184.52	**13**	1152.32	**23**	1109.74	**33**	1138.29
4	1147.48	**14**	1147.81	**24**	1142.11	**34**	1183.09
5	1082.13	**15**	1141.16	**25**	1098.00	**35**	1149.33
6	1063.95	**16**	1083.19	**26**	1148.54	**36**	1161.95
7	1104.84	**17**	1142.30	**27**	1139.52	**37**	1150.21
8	1081.56	**18**	1108.22	**28**	1110.12	**38**	1123.18
9	1112.74	**19**	1074.85	**29**	1097.44	**39**	1141.04
10	1142.89	**20**	1156.08	**30**	1189.91	**40**	1139.90

Table 3
(continuation)

Sample	ρp kg/m³	Sample	ρp kg/m³	Sample	ρp kg/m³	Sample	ρp kg/m³
1	1054.36	11	1076.42	21	1050.85	31	1087.29
2	1081.22	12	1055.38	22	1071.35	32	1127.86
3	1131.65	13	1061.23	23	1058.52	33	1084.18
4	1115.34	14	1065.50	24	1088.11	34	1116.16
5	1026.61	15	1068.50	25	1022.91	35	1084.29
6	995.69	16	1035.08	26	1079.73	36	1086.56
7	1054.88	17	1073.84	27	1072.83	37	1057.42
8	1025.51	18	1042.62	28	1037.97	38	1046.16
9	1050.76	19	954.70	29	1035.55	39	1069.40
10	1085.66	20	1080.52	30	1127.15	40	1060.46

Table 4

Results obtained after conducting the experimental researches for the initial moisture of 16%

Sample	ρp kg/m³	Sample	ρp kg/m³	Sample	ρp kg/m³	Sample	ρp kg/m³
1	877.31	11	883.94	21	888.93	31	904.33
2	878.85	12	914.85	22	907.83	32	903.63
3	901.85	13	878.48	23	898.29	33	893.84
4	901.20	14	875.92	24	900.47	34	889.25
5	902.85	15	884.28	25	910.78	35	897.43
6	910.72	16	901.87	26	886.71	36	901.72
7	904.28	17	907.20	27	917.24	37	884.62
8	909.75	18	889.84	28	879.39	38	871.59
9	891.28	19	885.40	29	888.86	39	893.74
10	907.28	20	864.96	30	894.62	40	905.70

From tables 2-4, it can be noted that pellet density decreases as the moisture of the raw material increases, from an average density of 1132.26 kg/m³ for a 10% material moisture, to 1065.01 kg/m³ for the 13% material moisture and dropping down to 894.78 for the 16% material moisture.

Following the experimental research, the theoretical data resulting from the models described in relations (1) and (3) were calculated for the input and control parameters of the pelleting process on the ring die equipment. Figure 3 shows a graphical comparison between the experimental data and the data calculated using relation (1).

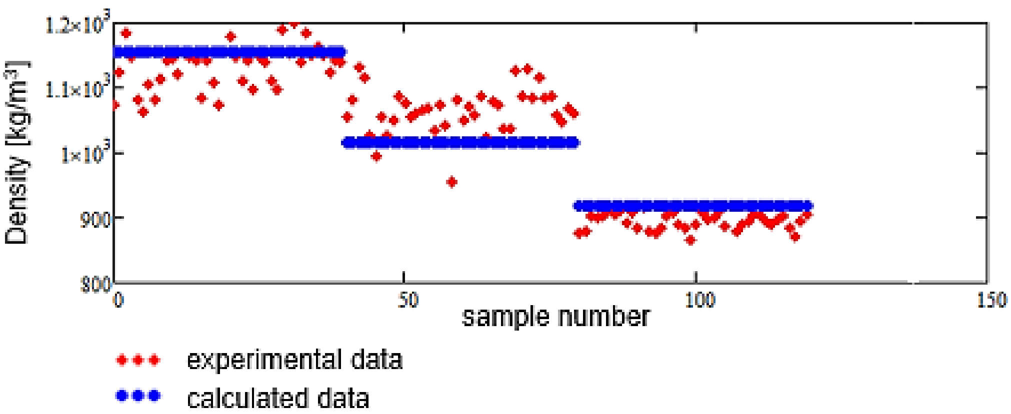

Fig. 3 – Comparative graphical representation of the experimental data obtained with the pelleting equipment and of the data calculated using relation (1)

From figure 3, a strong correlation can be observed between the data calculated using relation (1) and the experimental data.

Figure 4 shows the dependence of the pellet density on the input and control parameters for the model in relation (1).

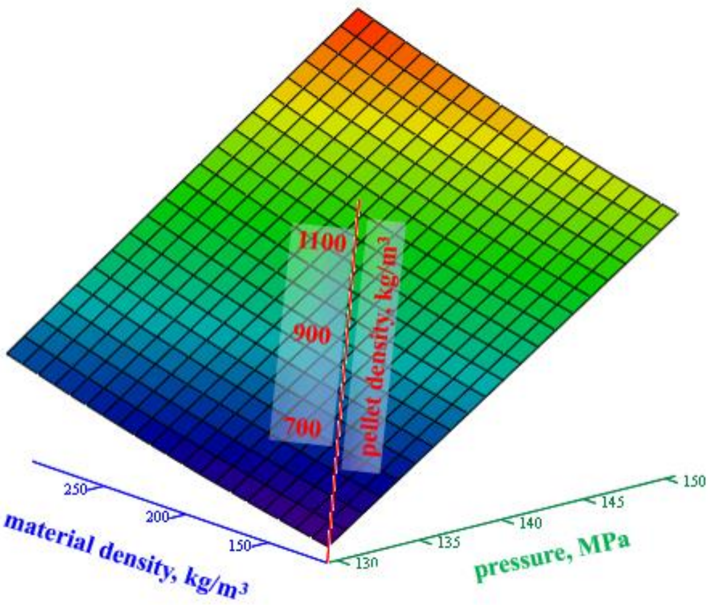

Fig. 4 - Dependence of pellet density on the maximum pressure and the density of the sawdust for the samples obtained using the ring die pelleting equipment for model (1)

The diagram shows that as the density increases (the initial moisture of the material increases), the density of the pellets decreases regardless of the value of the compression pressure.

Figure 5 shows a graphical comparison between the experimental data and the data calculated using relation (3).

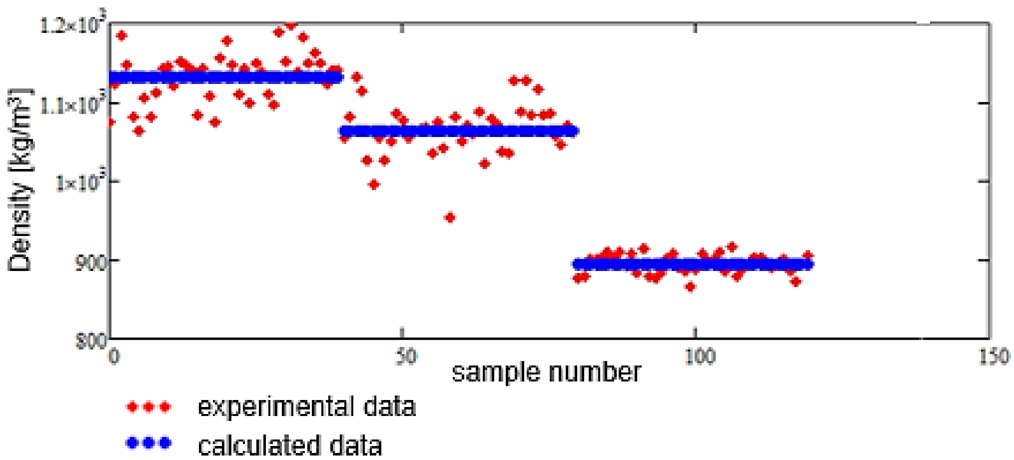

Fig. 5 - Comparative graphical representation of the experimental data obtained with the pelleting equipment and of the data calculated using relation (3)

From figure 5, an even stronger correlation can be observed between the data calculated using relation (3) and the experimental data, compared to results obtained for relation (1).

Figure 6 shows the dependence of the density of pellets on the compression pressure and the density of the raw material, for relation (3).

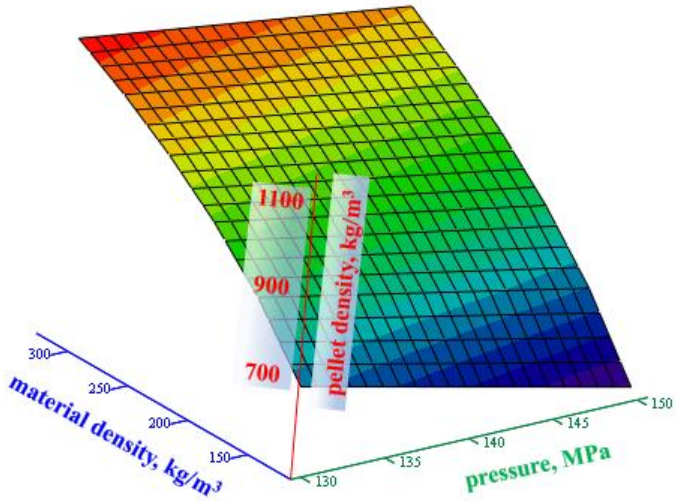

Fig. 6 - Dependence of pellet density on the maximum pressure and the density of the sawdust for the samples obtained using the ring die pelleting equipment for model (3)

The diagram shows, as in the case of the first model, that when the density increases, the density of the pellets decreases even at higher values of the compression pressure.

CONCLUSIONS

The densification of biomass depends on the complex interaction between the material properties and the parameters characteristic to the equipment used for densification. The mathematical models developed for the compaction process help to present the behaviour of the particles during the compaction process and can help optimize the parameters to obtain good quality products.

After conducting the experimental research and validating the two proposed mathematical models for the data obtained using the pelleting equipment with the fixed ring die, a strong correlation was found between the experimental data and the data estimated theoretically, $R = 0.911$ for model 1 and $R = 0.935$ for model 2.

An important conclusion found after conducting the experiments is that material moisture greatly influences pellet quality. Density decreased on average by 6 % for pellets obtained using material with 13% initial moisture compared to those obtained with material having 10% initial moisture and by almost 21% for pellets obtained from material with 16% initial moisture compared to the 10% initial moisture ones.

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