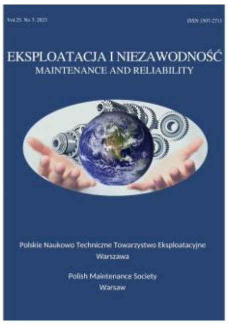

Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 25 (2023), Issue 3

journal homepage: http://www.ein.org.pl

Article citation info:
Baiul K, Vashchenko S, Khudyakov O, Bembenek M, Zinchenko A, V. Krot P, Solodka N, A Novel Approach to the Screw Feeder Design to Improve the Reliability of Briquetting Process in the Roller Press, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2023: 25(3) http://doi.org/10.17531/ein/167967

Indexed by: Web of Science Group

A Novel Approach to the Screw Feeder Design to Improve the Reliability of Briquetting Process in the Roller Press

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Highlights

- A novel approach is developed for the screw feeder design to improve overall reliability.
- A new mathematical model and an algorithm of design are developed to avoid overloading.
- The briquetting process is investigated by the example of two fine-grained materials.
- The compaction ratio of the peat is increased by 22-27% and hydrolyzed lignin – by 14-17%.
- The dependence of torque and drive power on screw feeder parameters is investigated.

Abstract

The screw feeder design for the pre-compaction of bulk materials to be briquetted in a roll press is considered to increase the overall reliability. The relationship between the parameters of the screw feeder and its technological characteristics is investigated by the example of two fine-grained materials. A new mathematical model and design algorithm have been developed, which takes into account the properties of materials, the roller press parameters, the shape of the briquettes, and their deformation after compaction. The relationship between the pre-compaction pressure and the material stack height at the inlet is determined. The relations between the torque, the screw pitch, and the material stack height above the inlet, as well as the drive power and the screw pitch on productivity, are investigated. In experiments, using the proposed design, the compaction ratio of the peat increases by 22-27%, and hydrolyzed lignin – by 14-17%. The proposed approach allows for preventing drive overloading and ensures the reliable operation of pre-compaction devices for the roller presses.

Keywords

fine-grained materials, briquetting, roller press, screw feeder, optimal design, compaction coefficient

1. Introduction

Maintaining the reliable and efficient functioning of mining, metallurgical and chemical enterprises is one of the important challenges in the modern economy [23,3,30,31]. Roller presses with profiled rollers are widely used in the briquetting processes of fine-grained raw materials in various industries [4,9,35,7,8]. Under certain technological conditions, the roller presses can be equipped with mechanical devices for feeding material into the gap between the rolls. Although some methods of briquetting process optimization, design changes, advanced simulation and visualization [2] techniques have been proposed, the production of high-quality briquettes still remains a challenge.

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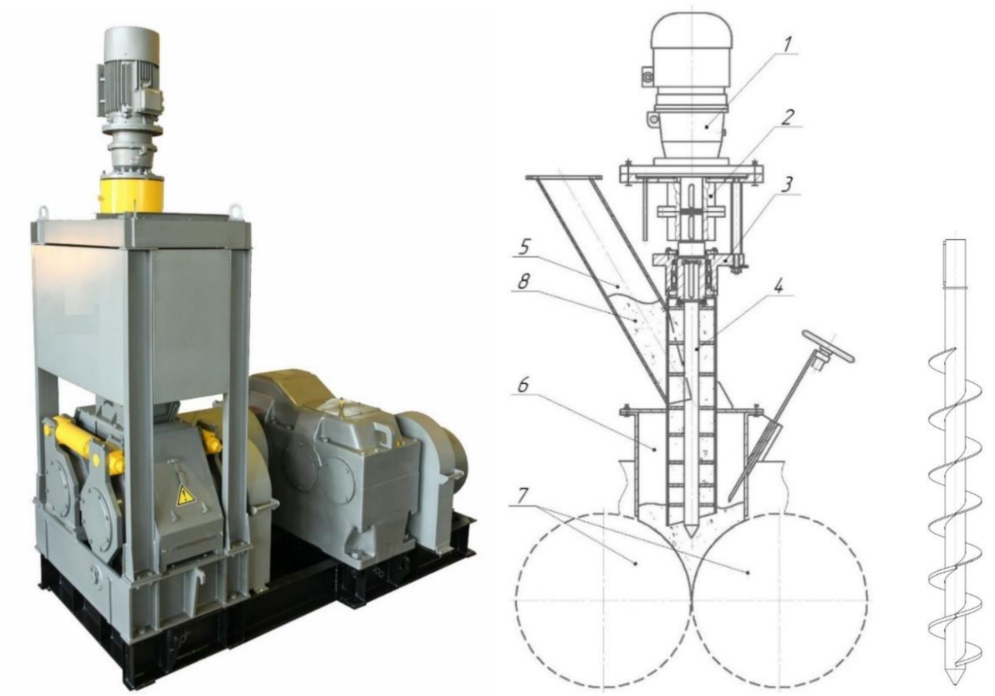
The use of a feeder pre-compaction device is necessary for the production of briquettes from materials with low bulk density ($\rho_{bulk} \leq 0.6$ g/cm^3), requiring forced material feeding into the gap between the rollers. Such materials are prone to fluidization, sagging and bridging during gravitational feeding to the deformation area [10]. Typically, to obtain high-quality briquettes the materials should have a compaction factor *Ky* equal to or greater than 3.0 (units). The compaction factor *Ky* of a material is the ratio of the density of the formed briquette ρ_{br} to the bulk density ρ_{bulk} of the original material, which is investigated in work [14] for different raw materials. The most used devices in the practice of roller briquetting process for forced feed and pre-compaction of fine fraction materials are the pre-compaction screw feeders. They can be equipped, subject to technological conditions, with different types of screws – cylindrical, conical, and complex, including as well as screws with a constant and variable pitch. Figure 1 shows a general view of a roller briquetting press equipped with a screw feeder.

These two components of the whole technological complex – roller press and screw feeder – are subjected to severe loads and abrupt failures in a case when their design parameters and working characteristics are not adjusted to each other. Prevention of drive overloading and meeting strict demands for quality of briquettes requires accounting properties of compacted material in the design algorithms and procedures among other values. Moreover, the problem of these machines overloading becomes even more complicated due to the gradual wear of rolls' profiles during roller press operation.

Despite existing clues and mathematical models, the main problem in designing screw feeders for roller presses is the lack of an effective systematic approach to defining their design and power parameters. When designing a screw device, some interrelated factors should be taken into account. At the same time, the range of applications of roller presses equipped with pre-compaction screw feeders for briquetting new types of fine fraction materials is constantly expanding. Therefore, the improvement of the existing mathematical models and the development of a new method for determining rational parameters of pre-compaction screw feeders for roller presses is very important.



a) b) c)

Figure 1. Roller press with screw feeder: (**a**) general view; (**b**) scheme of pre-compaction screw feeder: 1 – gear motor; 2 – coupling; 3 – support-bearing assembly of the screw feeder; 4 – screw; 5 – loading section of the screw feeder; 6 – roller press feeder; 7 – rollers of roller press; 8 – consolidated material; (**c**) general view of the screw.

There are quite a few publications on the study of the relationship between the design and technological parameters of screw feeders of roller presses. Probably, this is caused by the complexity of investigating the deformation area of a roller press equipped with a screw feeder and competition between manufacturers of roller presses. Quite often the selection of rational parameters of screw feeders of roller presses is based on the experimental results [6,5,27,34,18,21].

Dec and Komarek [6] introduced experimental tests of a screw feeder system in the roller press using some specific experimental devices. This experimental study provided information that helped understand the feeding and pre-compaction process that can be useful when developing new mathematical models of the pressing process, especially for the mathematical model verification.

The research presented by Dai and Grace in [5] was conducted to find the mechanisms of blockage in screw feeding and to determine the effects of particle mean size (0.5-15.0 mm), size distribution, shape, moisture content (10-60%), density and compressibility on biomass particle feeding at room temperature. The results of these experimental studies showed that large particles, wide size distributions, large bulk densities and high moisture contents generally led to larger torque requirements for screw feeding. It was also detected that the “choke section” and seal plug are important for the determination of the required torque.

In [27], the capacity of a screw feeder and the capacity of a high-pressure roller mill equipped with it with quartz materials were analyzed. It was shown the following. 1) The feeder capacity is proportional to the screw speed and does not depend on the counter-pressure created by varying the outlet resistance. 2) The mill capacity at different roller velocities is proportional to the screw speed. 3) The screw speed has to exceed the lower limit to ensure proper mill operation and this limit depends on the feed fineness; the capacity of screw feeders can be doubled at the same roller velocity. 4) The additional power draft can be kept at less than 10% of the total power if the screw speed is adjusted properly. The results of these studies may be useful for the development of experimental methods for evaluating the efficiency of calculation models of screw feeders of roll presses.

In [34], the influence of vacuum on the process of roller compaction of powders with the extremely poor flow is examined. This influence for materials under consideration is qualitatively correlated with the sensitivity of their bulk densities to the pressure. The impact of bulk density, roller gap, and deaeration (vacuum level) on the roller compaction process are investigated. Detailed information about the ability of powder processing helps to determine how the use of the vacuum line may improve the roller compaction process by screw feeders.

The study described in [18] analyzed statistically a pharmaceutical compaction process using an industrial-scale roller compactor. The roll speed was kept constant and the gap between rollers was uncontrolled. Microcrystalline cellulose was used as a model material. Some significant process parameters were determined, such as the screw speed to roll speed ratio and the roll pressure. The relationships between the process parameters and the resultant ribbon/granule/tablet characteristics were established.

A common feature of these studies [6-21] is that they are experimental and include statistical processing of the obtained results. At the same time, no universal mathematical model of the process of material compaction in a roll press equipped with a screw feeder has been proposed.

There are some papers studying the processes in screw conveyors and feeders operating as separate devices using mathematical tools [36,24,32,25,11,12,13].

In the paper [36], the discrete element method is used to simulate and analyze powder transportation. A 3D model of the screw conveyor is created and imported into the EDEM simulation software. The key parameters of a screw conveyor are the internal diameter of the screw, pitch and speed as design variables. The purpose of the research was to find the optimal operation modes of the screw conveyor. A specific practical problem for one material was solved. The results of this study allow making a solution to similar problems for determining the rational parameters of roller presses equipped with screw feeders.

In [24], it was examined how operating conditions influence the performance of a screw conveyor by applying the Discrete Element Method (DEM). A single-pitch screw conveyor with periodic boundary conditions was simulated. The DEM modelling gives predictions of screw conveyor performance in terms of variations of such parameters as particle speeds, mass flow rate, energy dissipation and power consumption, due to changes in the operating conditions.

In [32], a numerical analysis was carried out using the three-dimensional discrete element method (DEM) to study the performance of screw conveyors. The modelling of horizontal and vertical types of screw conveyors was studied. The results are compared with previous work and empirical equations.

The study [25] concerns screw conveyors with fully enclosed tubular casings. A theoretical approach to predict the performance of screw conveyors of any given geometry is presented. The influence of flow properties of loose material on conveyor performance was studied.

The above-mentioned studies indicate that the DEM is a promising tool for researching screw mechanisms requiring calibration of bulk material model [11] after which it can be conducted the optimization of a screw conveyor's exploitation parameters [12] by simulation of the real conditions [13]. Nevertheless, methods, in which the grained material is considered as a continuous loose isotropic material, are also being developed and are actively used in scientific and engineering calculations. This indicates the validity and relevance of the research presented in this work.

The main purpose of this paper is to create a new approach to the calculation and selection of the parameters of the screw feeder of a roller press to prevent overloading of both machines and provide their reliable operation within the whole technological complex and the high quality of output product (briquettes). The results of these studies can be used as a basis for the development of calculation and analysis methods of screw feeders for roller presses. At the same time, taking into account specific conditions of the deformation area of the roller press equipped with a device for forced feed and pre-compaction of the material constitute the innovation of this research and developed design method.

2. Method of model-based design the parameters of the roller press screw feeder

Before proceeding with the design, analysis and selection of the parameters of the roller press screw feeder, the conditions of its use should be defined based on the physical and mechanical properties of the material to be briquetted [15-22].

In [22], a graph analytical method for determining the type of device for feeding fine-grained charge material into a roller press is proposed by Kosturkiewicz. The essence of this approach is as follows: the compaction characteristics of the fine-grained material are determined experimentally, and the dependency curve of compaction factor Ky on compression pressure p is plotted. Next, the preferred method of feeding the fine-grained charge material into the deformation area based on the following conditions is to be chosen:

gravitational feed:

$$Ky_{br.max} \leq 2.0 \tag{1}$$

screw feeder with a cylindrical screw:

$$2.0 \leq Ky_{br.max} \leq 2.6 \tag{2}$$

screw feeder with a conical screw:

$$2.6 \leq Ky_{br.max} \tag{3}$$

where $Ky_{br.max}$ – maximum possible compaction coefficient of the fine-grained material to be briquetted.

In practice, it often happens that when briquetting materials in a roller press with pre-compaction by screw feeders equipped with cylindrical screws, the value of the compaction factor becomes more than 2.6. At the same time, there are some difficulties in using conical screws, namely, high manufacture cost, and frequent material jamming in the screw channel when changing the physical and mechanical properties of the material handled. Therefore, unless otherwise specified, the use of pre-compaction screw feeders with cylindrical screws is completely justified for most low bulk density materials ($\rho_{bulk} \leq 0.6$ g/cm^3). Therefore, in this work, the parameters of pre-compaction feeders with a cylindrical screw are investigated. In addition, a serious drawback of the models proposed by Kosturkiewicz in works [15-22] is the omission of the effect of feeding the material to the screw feeder and the impact of the geometry and parameters of the roller press operation on the operation of the screw feeder. Analysis shows that conditions (1-3) are empirical, and there is no clear justification for them. Therefore, other principles for choosing the type of material feeding to the deformation centre should be found proposed.

It is known from the practice of pressing fine-grained materials that it is very difficult to achieve compact body density, as a rule, the maximum density achieved is 5…15%

less than the density of a compact body made of this material. The choice of the appropriate scheme of material feeding into the gap between the rollers depends on the possibility of achieving the maximum value of the compaction coefficient that is determined by the expression:

$$Ky_{br.max} = \frac{\rho_{pikn}}{\rho_{bulk}} \quad (4)$$

where ρ_{pikn} – picnometric (true) density of fine-grained material particles, g/cm^3; ρ_{bulk} – bulk density of fine-grained material, g/cm^3.

The feeding scheme of the material in the rollers is selected depending on what degree of compaction can be achieved with a particular feeding scheme in a particular case and after comparing it with the maximum value, these conditions can be presented as follows:

gravitational feed:

$$Ky_{roll.max} \geq Ky_{br.max} \quad (5)$$

pre-compaction screw feeder:

$$Ky_{roll.max} \leq Ky_{br.max} \quad (6)$$

where $Ky_{roll.max}$ – the maximum possible coefficient of charge compaction in the deformation area [1]:

$$Ky_{roll.max} = 1 + \frac{D_0 \cdot (1 - cos\alpha_0)}{H_{br}}, \quad (7)$$

where D_0 – is the reduced diameter of press rolls, mm; H_{br} – is the thickness of the briquette on the rollers centres line, mm.

Parameter α_0 is the maximum pressing angle that can be determined by the specific parameters of the rollers seizing the charge material pick-up:

for rollers with toothed-grooved forming elements [1]:

$$\alpha_0 = arcsin \frac{1}{D_0} [\frac{D_0}{2} \cdot sin\alpha_{ch} + (\frac{D_0}{2} + (H_{br} - \delta_{roll})) \cdot sin\alpha_c -$$

$$-(D_0 + H_{br} - \frac{D_0}{2} \cdot cos\alpha_{ch} - (\frac{D_0}{2} + H_{br}) \cdot cos\alpha_c) \cdot tg\theta] \quad (8)$$

for rollers with symmetrical forming elements (lenticular, pillow-shaped) [1]:

$$\alpha_0 = arcsin\left(sin\alpha_c - \left(1 - cos\alpha_c + \frac{\delta_{roll}}{D_0}\right) \cdot tg\theta\right), \quad (9)$$

where δ_{roll} – the gap between the rollers, mm; θ – slope angle of the sliding lines, degree; α_c – extreme feed angle for a row of grooved forming elements, degree:

$$\alpha_c = arctgf_2 + arctg\xi \quad (10)$$

where f_2 – internal friction coefficient,

$$\alpha_{ch} = arctgf_1 + arctg\xi \quad (11)$$

where α_{ch} – extreme feed angle for a row of grooved forming elements, degree; f_1 – external friction coefficient; ξ – lateral pressure coefficient:

$$\xi = \frac{1 - sin\varphi_2}{1 + sin\varphi_2} \quad (12)$$

The values of the coefficients of external f_1 and internal f_2 friction are determined according to the experimental procedure.

The authors have developed their method for analyzing the process of pressing fine fractional materials and calculating the parameters of the briquetting process and a further selection of design parameters of press equipment. Namely, they use a functional relationship between pressing pressure p and compaction coefficient Ky that was established experimentally and described analytically [14]. According to this method, the power function is used for describing this relation, thus, this relationship can be written as follows:

$$p = a \cdot Ky^b, \quad (13)$$

where a and b – coefficients in the equation of approximation of the experimentally established compression curve of fine fraction charge, indicating the degree of its compression resistance; Ky – compaction factor, can be determined as:

$$Ky = \frac{\rho_{br}}{\rho_{bulk}}, \quad (14)$$

where ρ_{br} – briquette density, g/cm^3 .

However, equation (13) cannot be used to determine the pressing parameters in the low-pressure range (up to 5 MPa), which is typical for material output from the screw feeder. Therefore, an exponential function is used in this work to describe the experimentally established compression curve for describing the behaviour of the material in the screw feeder, as follows:

$$p = a \cdot e^{(c \cdot Ky)} + b \quad (15)$$

where a, b and c – coefficients in the approximation equation of the compaction curve of fine-grained material.

To make the briquetting process in the roller press with a screw feeder more stable, the condition of a constant flow rate of the briquetted charge material must be strictly met, which means, both the roller press and screw feeder productivity should match each other:

$$Q_{pr} = Q_{scr} \quad (16)$$

where Q_{pr} – roller press productivity, t/h; Q_{scr} – screw feeder productivity, t/h and

$$Q_{pr} = Q_{scr} = k_Q \cdot Q_{scr.req} \tag{17}$$

where $Q_{scr.req}$ – required productivity of the screw feeder, t/h and k_Q – productivity coefficient that can be determined as:

$$k_Q = 8760/T_e \tag{18}$$

where 8760 – number of hours per year; T_e – number of press working hours per year.

As a rule, the value of k_Q is within the range of 1.1-1.5, therefore, taking into account the practice of roller presses operation in real production conditions, k_Q =1.1 is accepted.

The required productivity of the screw feeder can be calculated as:

$$Q_{scr.req} = \frac{\pi \cdot (D_{scr}^2 - d_{scr}^2) \cdot (S_{scr} - S_0) \cdot \eta_3 \cdot 60 \cdot n_{scr} \cdot \psi \cdot \rho_{bulk}}{4 \cdot 10^9} \tag{19}$$

where D_{scr} – external diameter of the screw, mm; d_{scr} – inner screw diameter (screw shaft diameter), mm; S_{scr} – screw helix pitch, mm; S_0 – thickness of the screw belt in the axis direction, mm; η_3 – coefficient taking into account the axial advancement of the material depending on the angle of the screw line of the screw; n_{scr} – screw rotation frequency, min^{-1}; $\psi \leq 1$ – filling coefficient of the screw turns; $4 \cdot 10^9$ – coefficient that takes into account the units of measurement,

$$\eta_3 = \frac{\eta_1 + \eta_2}{2} \tag{20}$$

where η_1 – coefficient reflecting the axial movement of the material depending on the angle of inclination of the screw helical line in diameter D_{scr}:

$$\eta_1 = \frac{cos\alpha_D \cdot cos(\alpha_D + \varphi_1)}{cos\varphi_1 + sin\alpha_D \cdot sin(\alpha_D + \varphi_1)} \tag{21}$$

and η_2 – coefficient reflecting the axial movement advancement of the material depending on the angle of inclination of the screw helical line in diameter d_{scr}:

$$\eta_2 = \frac{Cos\alpha_d \cdot Cos(\alpha_d + \varphi_1)}{(1 + \frac{f_s}{f_c}) \cdot Cos\varphi_1} \tag{22}$$

where α_D – the angle of inclination of the screw helical line on the outer diameter D_{scr}; α_d – the angle of inclination of the screw helical line of the inner diameter d_{scr}; φ_1 – the angle of external friction determining the direction of movement of the material in the screw; f_s – dynamic coefficient of friction of the material on the screw surface; f_c – dynamic coefficient of friction of the material on the screw body.

So, based on stated in [33] and the fact that the movement of the material along the screw feeder belt and the body of the press is determined by the conditions of external friction, it is assumed that:

$$f_s = f_c \approx 0.7 f_1 \tag{23}$$

the pitch of screw helix line S_{scr} is:

$$S_{scr} = \pi \cdot D_{scr.e} \cdot tg\alpha_e \tag{24}$$

where α_e – the angle of inclination of the screw helical line on the effective diameter, degree and $D_{scr.e}$ – effective screw diameter, mm can be calculated as:

$$\alpha_e = arctg \frac{S_{scr}}{\pi \cdot D_{scr.e}} \tag{25}$$

and

$$D_{scr.e} = \sqrt{\frac{D_{scr}^2 + d_{scr}^2}{2}} \tag{26}$$

correspondingly.

The values of α_D, α_d and φ_1 angles are defined as follows:

$$\alpha_D = arctg \frac{S_{scr}}{\pi \cdot D_{scr}}; \alpha_d = arctg \frac{S_{scr}}{\pi \cdot d_{scr}}; \varphi_1 = arctg \frac{f_c}{\pi \cdot D_{scr}} \tag{27}$$

The pressure in the charge after leaving the screw in the area of the material seizure by the press rollers is the pre-compaction pressure of the material and is determined according to the following expression [29,28]:

$$p_{scr} = p_{pc} = p_0 \cdot exp\left(-\frac{[b_{scr} \cdot f_c \cdot cos\,\omega - (b_{scr} + 2 \cdot h_{scr} + b_{scr} \cdot f_c \cdot sin\,\omega) \cdot f_s]}{b_{scr} \cdot h_{scr} \cdot sin\alpha_e} \cdot l_{scr}\right) \tag{28}$$

l_{scr} – length of the working part of the screw in (28) (it is based on analytical studies in [32,25]), mm; h_{scr} is the height of screw coil, mm; and b_{scr} is screw width, mm that can be determined as:

$$b_{scr} = \pi \cdot D_{scr.e} \cdot sin\alpha_e \tag{29}$$

p_0 – initial pressure in the material at the screw feeder inlet, MPa:

$$p_0 = h_{bulk} \cdot \rho_{bulk}, \tag{30}$$

where h_{bulk} is the height of the material stack above the screw feeder inlet, mm and ω is the angle between the direction of movement of the material and the surface of the helical line of the screw, degree, can be determined as:

$$\omega = arctg \frac{cos^2\alpha_e - 0.5}{sin\,2\alpha_e} \tag{31}$$

Compaction coefficient of the material in the roller press using the screw feeder:

$$Ky_{br} = Ky_{pc} \cdot Ky_{roll}, \tag{32}$$

where Ky_{pc} – is the pre-compaction coefficient of the material after leaving the screw feeder, at the entrance to the area of the material seizure by rollers; Ky_{roll} – coefficient of material compaction by the press rollers, which is determined by the geometric parameters of the deformation area in the roller press [34,18]:

$$Ky_{roll} = 1 + \frac{D_0 \cdot (1 - cos\alpha_{pr})}{H_{br}}, \quad (33)$$

where D_0 – press rollers reduced diameter, mm; H_{br} – the briquette thickness on the rolls centres line, mm; α_{pr} – pressing angle, deg.

For working conditions of the press with the screw feeder, it is accepted:

$$\alpha_{pr} = \alpha_0 \quad (34)$$

Determining the value of the material compaction by rolls according to expressions (33) using the values of geometric parameters of the rolls forming the elements of the press and expressions (15, 23, 26-30) it becomes possible to determine the value of the previous seal Ky_{pc}:

$$Ky_{pc} = \frac{1}{c} \cdot log\left(\frac{a}{p_{pc} - b}\right) \quad (35)$$

The density of briquettes taking into account the elastic aftereffect:

$$\rho_{br.1} = \frac{Ky_{br} \cdot \rho_{bulk}}{\frac{\delta_V}{100} + 1}, \quad (36)$$

where δ_V – elastic aftereffect, %.

The following condition is proposed to evaluate the efficiency of the adopted screw design:

$$p_{max} \geq 10 \cdot p_{pc} \quad (37)$$

$$l_{scr} \leq 5 \cdot S_{scr} \quad (38)$$

If the conditions (36, 37) are not met, it is necessary to make an assessment and analysis of the deviation and adjust the parameters α_e and l_{scr}.

When the conditions (37, 38) are met, the power parameters of the screw feeder can be determined as follows:

axial force on the screw, N:

$$F_{axis} = \frac{\pi \cdot (D_{scr}^2 - d_{scr}^2)}{4} \cdot p_{pc} \quad (39)$$

friction force in the feeder, N:

$$F_f = \frac{\pi \cdot (D_{scr}^2 - d_{scr}^2)}{4} \cdot \frac{l_{scr}}{S_{scr}} \cdot \frac{p_{pc} + p_0}{2} \cdot f_c \quad (40)$$

the moment on the screw shaft, N×m:

$$M_{scr} = (F_{axis} \cdot tg\alpha_e + F_f) \cdot \frac{D_{scr} + d_{scr}}{2} \cdot 10^{-3} \quad (41)$$

the moment on the shaft of the screw feeder electric motor, N×m:

$$M_{elm} = \frac{M_{scr}}{u_{scr.drive}} \quad (42)$$

where $u_{scr.drive}$ – gear ratio of the screw feeder drive.

Power consumed by the screw feeder, kW is calculated as:

$$N_{scr} = \frac{\pi \cdot M_{scr} \cdot n_{scr} \cdot 10^{-3}}{30 \cdot \eta_{scr}} \quad (43)$$

According to equations (1-43), the algorithm is developed (see Figure 2) of design, power, and technological parameters of the screw feeder calculation and the analysis.

Based on the proposed algorithm the computational and analytical studies of the screw feeder parameters for the conditions of briquetting certain materials such as brown coal, peat and lignin hydrolysis were performed. These materials have been selected based on the following properties, which are common to all of them:

- low bulk density (<1,0 g/cm^3);
- the value of the maximum compaction coefficient achieved Ky>2,0;
- all these materials are often used in the metallurgy and energy generation industry in briquette form as alternative sources of thermal energy.

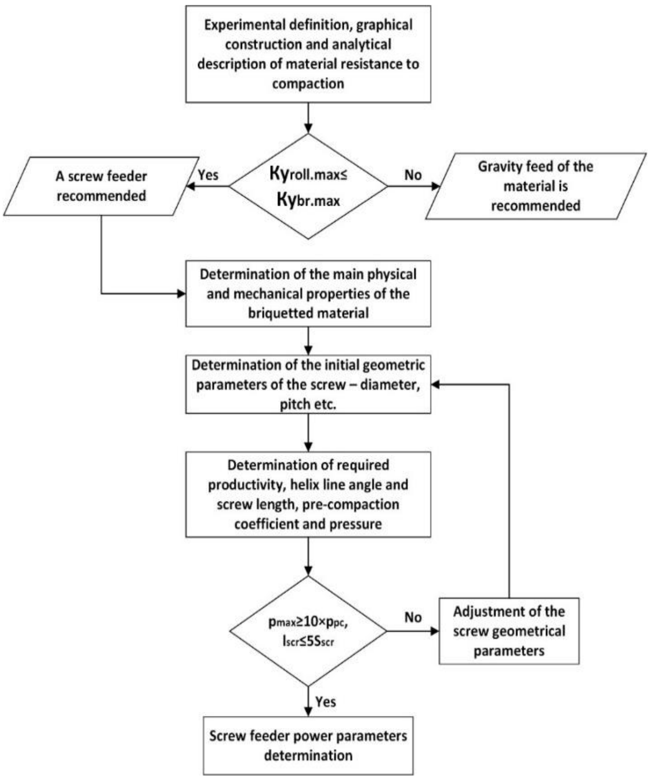


Figure 2. Algorithm for calculation and analysis of design, technological and power parameters of screw feeder of roller press.

Different physical and mechanical properties of these materials determine their particular behaviour when briquetting in roller presses. Table 1 shows the values of the physical and mechanical characteristics of the materials under investigation. These data are determined by experiments in this study.

Table 1. Physical and mechanical characteristics of the studied materials.

Name, unit	Material	
	Peat	**Hydrolytic lignin**
Fraction, mm	0-3	0-5
Coefficients of the compaction resistance equation $p=a\cdot e(-c\cdot Ky)+b$	a = 0.1495; b = -2.002; c = -2.058	a = 0.7416; b = -5.004; c = -1.66
Pycnometric particle density ρ_{pikn}, g/cm^3	1.55	1.50
Bulk density ρ_{bulk}, g/cm^3	0.43	0.48
Elastic aftereffect (average) δ_V, %	22.4	19.9
External friction coefficient f_1	0.78	0.85
Internal friction coefficient f_2	0.97	0.95
Lateral pressure coefficient ξ	0.178	0.184

The calculations performed based on the following parameters of the press rolls:

- forming elements design: saddle;
- forming element dimensions: 40.0x38.5x17.5 mm;
- press rollers diameter: 648mm;
- press rollers reduced diameter: 630.5 mm;
- width of the working roller surface: 200.0 mm;
- briquette thickness (excluding elastic aftereffect): 17.5 mm;
- gap between the rolls: 0.5 mm.

Design and operating parameters of the screw feeder:

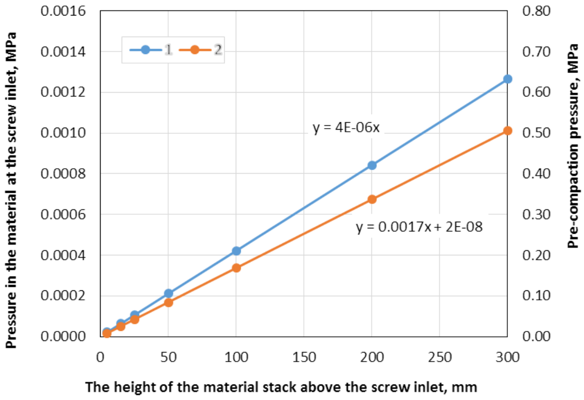
- outer diameter: 169 mm;
- shaft diameter: 60 mm;
- working length: 400 mm;
- tape average thickness: 4 mm;
- pitch: 100-140 mm;
- feeder drive gear ratio: 8.3;
- feeder drive efficiency: 96 %;
- rotation speed: 112, min^{-1};
- filling factor of the screw turns: 0.8.

3. Results of Calculation on the Model

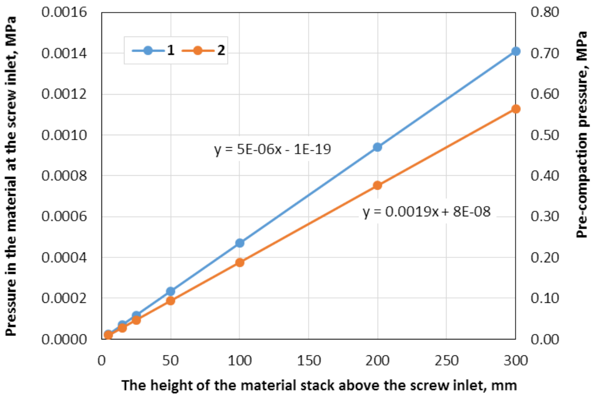
Using expressions (1-43) for the received parameters of rolls and screw calculations were performed and several data sets were obtained. They allow analyzing dependence between working parameters of the screw feeder accepted in work at briquetting of the materials specified in Table 1.

The main parameter that determines the efficiency of the screw feeder is the pre-compaction pressure and the degree of its effect on the total degree of material compaction in the roller press. The pre-compaction ratio is significantly affected by the height of the material column at the screw entrance. Graphs in Figures 3 and 4 allow evaluation of the influence of the material stack at the screw inlet on the sealing characteristics of the material.

The data in Figure 3 show that as the height of the material column increases, the pressure at the inlet to the screw increases. It improves the filling of the screw gap and significantly increases material pre-compaction pressure in the roller grip area.



a)

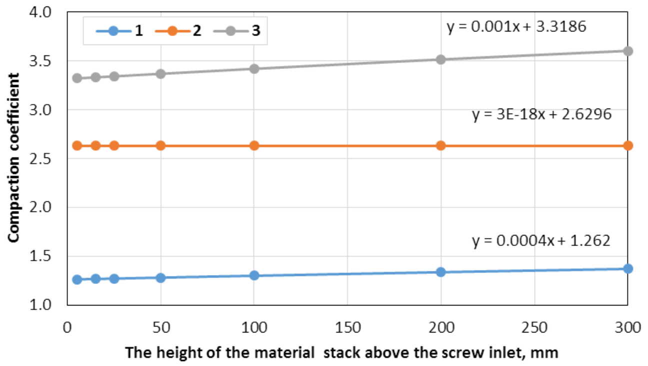


b)

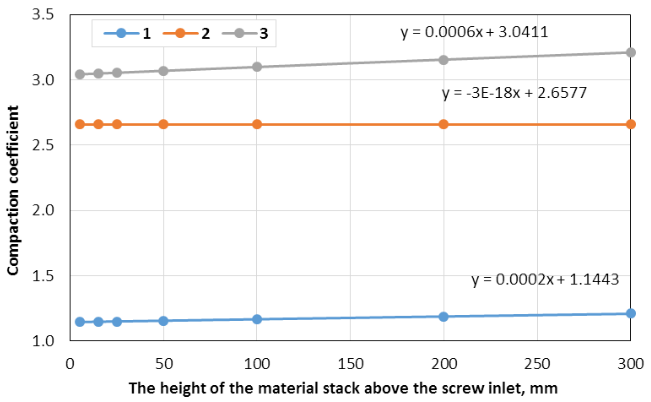
Figure 3. Influence of value of the material stack height in front of the screw on the pressure in the material at the screw inlet and in the area of the material capture by rolls at screw pitch 100 mm: 1 – material pressure at the inlet to the screw; 2 – pre-compaction pressure; (**a**) peat; (**b**) lignin.

The pre-compaction pressure at the material outlet from the screw feeder and its seizure by the rolls and the compaction pressure in the deformation area of the roller press determine the total value of the material compaction, expressed by the compaction coefficient.

Figure 4 shows graphs that allow estimating the screw feeder's contribution to the overall value of the material compaction coefficient in a roller press. These graphs show that using a screw feeder allows for increasing the value of the compaction coefficient of the studied peat, on average, by 22-27% and hydrolyzed lignin – by 14-17%.



a)



b)

Figure 4. Influence of the material column in front of the screw on the amount of material compaction at screw pitch 100 mm: 1 – pre-compaction; 2 – compaction in the rolls; 3 – the total amount of material compaction; (a) peat; (b) lignin.

Such values of compaction ratio increasing are essential and, as practice shows, allow to receive high-quality briquettes. At that time, in the absence of a screw feeder, the briquettes from the studied peat and lignin on a roller press could not be obtained.

Computational and analytical studies revealed that when the press and roller capacities are matched and there is no overpressure, screw pitch has little effect on the pre-compaction pressure. It is largely due to the physical and mechanical properties of the material and the size of its column at the screw inlet.

However, a change of the screw pitch affects the productivity of the screw feeder and the value of friction force of the charge against the walls of the feeder housing, and, consequently, the parameters of the power drive.

Figures 5 and 6 graphically show the dependency of the moment on the screw shaft on the size of its pitch for the materials under study (peat, hydrolysis lignin) and different sizes of the material column above the screw feeder inlet.

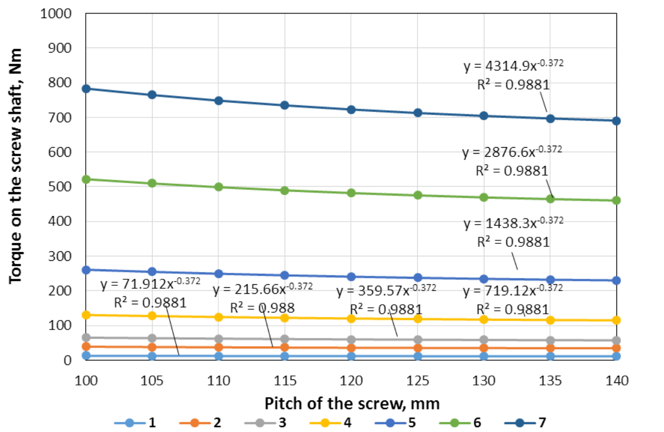


Figure 5. The relationship between the torque on the screw shaft, the pitch of the screw and the height of the material stack above the screw inlet: 1 – 5 mm; 2 – 15 mm; 3 – 25 mm; 4 – 50 mm; 5 – 100 mm; 6 – 200 mm; 7 – 300 mm; the material used – peat.

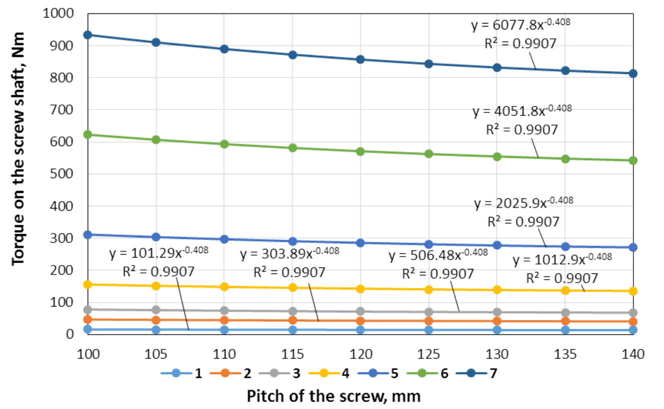


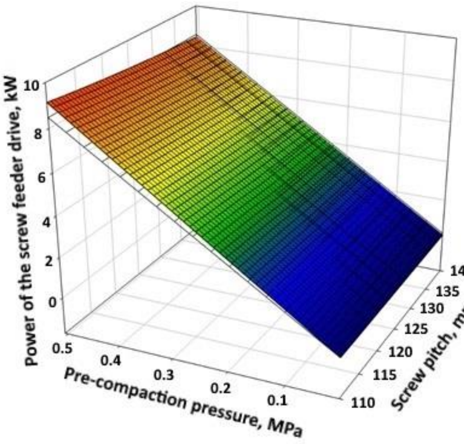
Figure 6. The relationship between the amount of torque on the screw shaft, the pitch of the screw height of the column of the material above the screw inlet: 1 – 5 mm; 2 – 15 mm; 3 – 25 mm; 4 – 50 mm; 5 – 100 mm; 6 – 200 mm; 7 – 300 mm; the material used – lignin.

These graphs show the character of increasing in torque on the shaft of the screw due to the increase in the height of the material column above the screw feeder inlet. The curves shown in Figures 5 and 6 are described with high accuracy by power, exponential and logarithmic equations. This allows them to be used to build predictive models of screw feeders of roller presses.

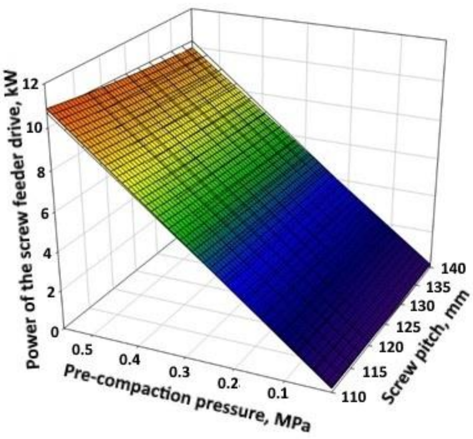
Approximation and analysis of the curves presented in Figures 5 and 6 by equations are as follows:

$$\mathrm{M}_{scr} = a_{l.scr} \times S_{scr}^{b.batch} \tag{44}$$

where $a_{l.scr}$ is an integral representation of the influence of design parameters of the screw feeder, and *b.batch* reflects the influence of physical and mechanical properties of the material to be briquetted.

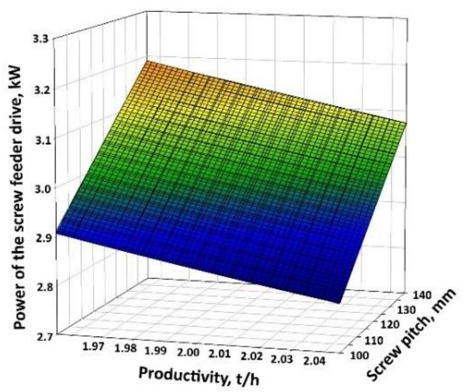


a)

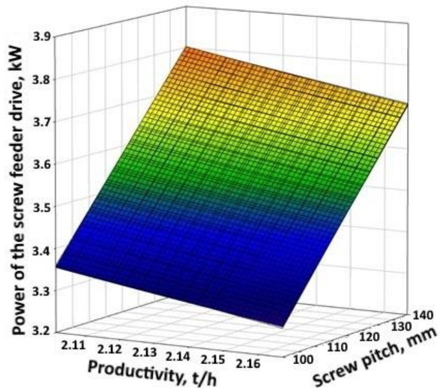


b)

Figure 7. Relationship between the power of the screw feeder drive, the screw pitch and the pre-compaction pressure at the height of the material column above the screw inlet – 100 mm; (a) peat; (b) lignin.



a)



b)

Figure 8. The relationship between the power of the screw feeder drive, the screw pitch and the productivity of the screw feeder, at the height of the material column above the screw inlet is 100 mm: (a) peat; (b) lignin.

Dependences graphically presented in Figures 7a and 7b are described by the following analytical expressions, respectively:

$$N_{scr} = 6.3691 - 0.0069 \times Q_{scr} - 1.2737 \times p_{pc}, R^2 = 0.97; \tag{45}$$

$$N_{scr} = 1.4364 - 0.0120 \times S_{scr} + 18.6909 \times p_{pc}, R^2 = 0.97. \tag{46}$$

Dependences presented graphically in Figures 8a and 8b are described by the following analytical expressions, respectively:

$$N_{scr} = 7.8405 - 0.011 \times Q_{scr} - 1.3983 \times S_{scr}, R^2 = 0.99; \tag{47}$$

$$N_{scr} = 7.405 - 0.011 \times Q_{scr} - 1.3983 \times S_{scr}, R^2 = 0.99. \tag{48}$$

Graphical dependences presented in Figure 7 and 8 and their description using analytical expressions (47,48) allows predicting the change of power and technological parameters (pre-compaction pressure and drive power etc.) of screw feeder taking into account physical and mechanical properties of briquetted material and screw design parameters. Similar forecast models using the computational and analytical tools developed in the work could be built for other variations of the parameters of screw feeder (graph coordinates), for example:

- pre-compaction pressure - pitch of the screw turns - torque on the screw shaft;
- size of the material stack above the screw feeder inlet – pitch of the screw turns – pre-compaction pressure;
- size of the material stack above the screw feeder inlet – pitch of the screw turns - moment on the screw shaft/power of the screw feeder's drive, etc.

The presented instructions for using the graphical and analytical method allow a reasonable choice of design and technological parameters of screw feeders of roller presses.

4. Industrial validation

Some tests using different materials were carried out on the roller press design similar to the one shown in Figure 1.

Main parameters of the roller press:

- maximum pressing force: 1500kN;
- forming elements design: saddle;
- forming element dimensions: 40.0x38.5x17.5 mm;
- press rolls diameter: 648mm;
- press rolls reduced diameter: 630.5 mm;
- width of the working roller surface: 200.0 mm;
- briquette thickness (excluding elastic aftereffect): 17.5 mm;
- gap between the rolls: 0.5 mm;
- roll speed: from 1 to 10 min^{-1} (adjustable by a frequency converter);
- nominal gearbox torque: 28.5 kN m;
- power supply: 55 kW.

Main parameters of the screw feeder:

- outer diameter: 169 mm;
- shaft diameter: 60 mm;
- working length: 400 mm;
- tape average thickness: 4 mm;
- screw length: changeable (a set of several screws);
- pitch: 91.2-150.0 mm;
- nominal screw rotation speed: 112 min^{-1} (and adjustable by a frequency converter);
- nominal gearbox torque: 870 Nm;
- power supply: 11 kW.

The main design parameters of the feeder and the press, except the variable length of the screw, are corresponding to those mentioned earlier. Figure 9 shows a general view of peat and the briquettes produced during these tests. The appearance of the briquettes from the hydrolyzed lignin as well as its feed material is similar.

a) b)

Figure 9. General appearance: (a) peat; (b) peat briquettes obtained on a roller press.

The data obtained in the process of work on the design, production, and exploitation of roller presses with screw feeders are presented in Table 2. It was difficult to bring these data into a well-structured form because they are obtained from the various tests of screw feeders supplied to the customers and not from planned lab experiments. The feature of the tests on real industrial equipment was that they were carried out in two modes of operation of the roller press with a screw feeder (see Table 2).

Table 2. Experimental and industrial pressing on roller presses using a screw feeder of an industrial roller press.

Screw type number	The average value of the screw step, mm	The number of turns of the screw	Material	Experimental data (Frequency of screw rotation, 112 min^{-1})				Calculated data (Frequency of screw rotation, 112 min^{-1})			
				Briquette density, g/cm^3	Torque on the shaft of the screw feeder motor, Nm	Moment on the shaft of the feeder screw, Nm	The power consumed by the feeder drive, kW	Briquette density, g/cm^3	Torque on the shaft of the screw feeder motor, Nm	Moment on the shaft of the feeder screw, Nm	The power consumed by the feeder drive, kW
1	91.2	7	peat	1.16-1.18	14.0-14.5	119.6-123.8	1.46-1.51	1.17-1.18	11.6-13.4	96.4-111.3	1.18-1.36*
1		7		1.16-1.18	14.5-15.0	123.8-128.1	1.51-1.56	1.18	13.4-20.1	111.3-167.0	1.36-2.04*
1		7		1.16-1.18	15.0-18.0	128.1-153.7	1.56-1.87	1.18-1.19	20.1-26.8	167.0-222.6	2.04-2.72*
1		7	lignin	1.03-1.24	15.0-17.0	128.1-145.0	1.56-1.77	1.22	14.0-16.1	115.9-133.8	1.42-1.64*
2	121.3	7		1.24-1.27	35.5-42.5	294.7-363.0	3.59-4.43	1.22-1.23	19.4-22.4	161.0-185.9	1.97-2.27*
3	150.0	6		1.21-1.24	41.0-43.0	350.1-367.2	4.28-4.48	1.23**	20.0-21.9	157.3-181.7	1.92-2.22*
4	132.8	4.5		1.21-1.24	21.0-26.0	179.3-298.9	2.13-3.65	1.22**	9.8-11.3	81.6-94.3	1.0-1.15
5	126.4	3.5		1.21-1.24	12.0-15.0	99.6-136.6	1.21-1.67	1.22**	6.0-6.9	49.7-57.5	0.61-0.70
6	118.0	2.5		1.00-1.10	9.0-10.0	76.9-85.4	0.94-1.04	1,21**	3.1-3.6	25.9-29.9	0.32-0.37
7	136.7	4.5		1.21-1.24	23.0-24.0	196.4-205.0	2.39-2.50	1.22-1.23**	10.2-11.8	84.7-97.8	1.03-1.19

* The screw length is too long, it should be recommended to adjust the α_e and l_{scr} parameters.

** During the startup process of the press, the preliminary backing up (retaining) the material was carried out

In the first mode, without preliminary support of the material – the press operates in normal mode. It prevents the material from being displaced from the deformation zone and creates

a pre-compaction pressure sufficient to achieve the required degree of material compaction. In this mode (Table 2), the experimental and calculated values of strength parameters and density of briquettes had a slight discrepancy. This confirms the theoretical positions stated above.

In the second mode, with preliminary support of the material – when the feeder was put into operation before the press rolls. This was done to create the so-called "initial plug", by analogy with extrusion moulding; the delay was 2-3 seconds. During this time, a small portion of the material was pressed into the space between the rolls. During the start-up of the rolls, a short-term overload of the drive was observed, but this did not lead to its emergency shutdown. Then the press switched to the nominal operating mode. This method allows for increasing the degree of compaction of the material, but at the same time, there was a significant increase in energy consumption parameters.

5. Discussion

As a result, comparing the data given in Table 2, we found that the data of theoretical calculations correlate quite well with the data obtained during the experiment, the discrepancy is, on average, up to 15%. Such good correlation allows using the developed models in strength capacity calculations and drives power estimation at the design stage of screw feeders depending on roller press productivity and the expected properties variation of the different fractions of briquetted materials.

It was determined that the most rational, in terms of technological and energy indicators of the briquetting process, is 3.5-4.5 turns of the screw. It has been proven that the height of the column of material at the entrance to the screw cavity has a significant impact on the performance characteristics of the screw feeder. The use of a screw feeder for the studied materials allows for increasing the degree of their compaction by 17-27%.

In the future, the results of the above theoretical studies could be expanded on a wider range of materials with different mechanical properties (granulometric composition, moisture content, bulk density, etc.). This will make it possible to improve the proposed method and more accurately determine its applicability limits.

6. Conclusions

A computational and analytical method has been developed to determine and evaluate the influence of the design parameters of the screw feeder and the physical and mechanical characteristics of the briquetted material on the compaction parameters and power characteristics of the screw feeder of the roller press. An algorithm for the implementation of this method has been also developed.

Taking into account the physical and mechanical properties of fine-grained materials and geometric parameters of deformation, the conditions for determining the need for a screw feeder in the roller press design are formulated. Under these conditions, the screw feeder or any other forced material feed and pre-compacting device can be used in the roller press, if the required (or maximum) degree of material compaction cannot be achieved by gravitational feed into the gap between rolls. Graphical and analytical relationships between design, power and other technological parameters of the screw feeder of the roller press that can be used for finding optimum design solutions are established.

The analytical studies and industrial measurements of the screw feeder parameters on the roller press were carried out. The obtained calculation and experimental data justify the theoretical provisions assumed and the method developed.

The results of this study allow us to prevent overloading of both screw feeder and roller press providing their reliable operation within the whole technological complex with the high quality of output product (briquettes).

References

1. Baiul KV. Effect of the geometrical parameters of roller press forming elements on the briquetting process: analytical study. Powder Metallurgy and Metal Ceramics 2012; 51: 157–164, https://doi.org/10.1007/s11106-012-9411-8
2. Bembenek M, Buczak M. The fine-grained material flow visualization of the saddle-shape briquetting in the roller press using computer image analysis. Journal of Flow Visualization and Image Processing 2021, 28, 2, 69-78, https://doi.org/10.1615/JFlowVisImageProc.2021035864
3. Best Practices and Perspectives of Energy-Efficiency Technologies for Utilization of Low Rank Coal within APEC Economies. Reports. SOM Steering Committee on Economic and Technical Cooperation(SCE), Energy Working Group (EWG), 2013; 89. [CrossRef]
4. Borowski G, Hycnar JJ. Utilization of fine coal waste as a fuel briquettes. Inernational Journal of Coal Preparation and Utilization 2013, 33:194-204, https://doi.org/10.1080/19392699.2013.787993
5. Dai J, Grace JR. Biomass granular screw feeding: An experimental investigation. Biomass & Bioenergy 2011; 35: 942–955, https://doi.org/10.1016/j.biombioe.2010.11.026
6. Dec RT, Komarek RK. Testing performance of roller force feed systems. 23rd Biennial Conference, Seattle, WA, IBA Proceedings, 1993; 23: 65–75.
7. Dec RT, Komarek RK. Computer aided design of roller type briquetters and compactors. 21st. Biennial Conference, New Orleans, LA, IBA Proceedings, 1989; 21: 35-38. https://doi.org/10.1016/0010-4485(89)90115-2
8. Dec RT, Komarek RK. Roll press design for powder and bulk solids. 15th Powder and Bulk Solids Conference/Exhibition, Proceedings of the Technical Program, June 4-7, O'Hare Exposition Center, Rosemont, IL, 1990; 125-136.
9. Hryniewicz M, Kosturkiewicz B, Janewicz A. Selected problems of development of construction and exploitation of roller presses (Wybrane zagadnienia doskonalenia konstrukcji i eksploatacji pras walcowych). Problemy Eksploatacji 2004; 4: 63-70. [CrossRef]
10. Johanson JR. Roll press feed systems. Powder Handling & Processing 1996, 8, 2, 159-163.

11. Karwat B, Machnik R, Niedźwiedzki J, Nogaj M, Rubacha P, Stańczyk E. Calibration of bulk material model in discrete element method on example of perlite D18-DN. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2019; 21(2): 351-357, http://dx.doi.org/10.17531/ein.2019.2.20
12. Karwat B, Rubacha P, Stanczyk E. Optimization of a screw conveyor's exploitation parameters. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2021; 23(2): 285–293, http://doi.org/10.17531/ein.2021.2.8
13. Karwat B, Rubacha P, Stanczyk E. Simulational and experimental determination of the exploitation parameters of a screw conveyor. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2020; 22(4): 741–747, http://dx.doi.org/10.17531/ein.2020.4.18
14. Khudyakov AY, Vashchenko SV. Analysis of known dependencies and construction of new compaction equations for fine materials of the mining and metallurgical complex. Refractories and Industrial Ceramics 2020; 60(6): 618-626, https://doi.org/10.1007/s11148-020-00417-z
15. Kosturkiewicz B. Badania obciążeń elementu roboczego zasilacza ślimakowego momentem skręcającym (Torsional torque testing of the working element of the worm feeder). Zeszyty Naukowe Politechniki Białostockiej. Nauki Techniczne. Budowa i Eksploatacja Maszyn 2002; 9: 235–242, [CrossRef]
16. Kosturkiewicz B. Matematyczny model obciążenia elementu roboczego zasilacza ślimakowego (Mathematical model of the load of the working element of the screw feeder). Automatyka: półrocznik Akademii Górniczo-Hutniczej im. Stanisława Staszica w Krakowie 2011; 15: 2, 247–254. [CrossRef]
17. Kosturkiewicz B. Modelowanie obciążeń elementu roboczego zasilacza ślimakowego siłą poosiową (Modeling loads on the working element of the worm feeder with axial force). In: Problemy w budowie i eksploatacji wybranych maszyn i urządzeń technologicznych. Hryniewicz M, Kochan E (eds). Kraków, WIMiR AGH, Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie. Wydział Inżynierii Mechanicznej i Robotyki; 2004; 23: 121–128.
18. Kosturkiewicz B. Pasmowy model przepływu materiału drobnoziarnistego w zasilaczu ślimakowym (Band model of fine-grained material flow in a screw feeder). Mechanika. Akademia Górniczo-Hutnicza im. Stanisława Staszica, Kraków 2000; 19(4): 439–448, [CrossRef]
19. Kosturkiewicz B. Zagadnienie doboru geometrycznych cech konstrukcyjnych ślimaków w urządzeniach do scalania drobnoziarnistych materiałów odpadowych (The problem of selection of geometric constructional features of screws in devices for consolidation of fine-grained waste materials). Zeszyty Naukowe Politechniki Białostockiej. Nauki Techniczne. Budowa i Eksploatacja Maszyn 2001; 139(8): 249–258. [CrossRef]
20. Kosturkiewicz B. Zagadnienie przepływu materiałów drobnoziarnistych w zasilaczu ślimakowym (The problem of the flow of fine-grained materials in a screw feeder). Problemy Maszyn Roboczych. Kolegium Twórczości Technicznej Akademii Inżynierskiej w Polsce 2001; 17: 135–143, [CrossRef]
21. Kosturkiewicz B, Janewicz A. Brykietowanie odpadowego grafitu w prasie walcowej z podajnikiem ślimakowym (Briquetting of waste graphite in a roller press with a screw feeder). Przemysł Chemiczny 2017; 96(8): 1691–1694. [CrossRef] https://doi.org/10.15199/62.2017.8.13
22. Kosturkiewicz B, Janewicz A, Hryniewicz M. Selection method for the roller press feeder. Journal of Machine Construction and Maintenance 2017; 3: 45-51, [CrossRef]
23. Mathieux F, Ardente F, Bobba S, Nuss P, Blengini G, Alves Dias P, Blagoeva D, Torres De Matos C, Wittmer D, Pavel C, Hamor T, Saveyn H, Gawlik B, Orveillon G, Huygens D, Garbarino E, Tzimas E, Bouraoui F, Solar S. Critical Raw Materials and the Circular Economy – Background report, EUR 28832 EN, Publications Office of the European Union, Luxembourg 2017; JRC108710, https://doi.org/10.2760/378123
24. Owen PJ, Cleary PW. Prediction of screw conveyor performance using the Discrete Element Method (DEM). Powder Technology 2009; 193: 274–288, https://doi.org/10.1016/j.powtec.2009.03.012
25. Roberts AW. Recent developments in feeder design and performance. Handbook of Powder Technology 2001; 10: 211-223, https://doi.org/10.1016/S0167-3785(01)80023-3
26. Sajjia M, Albadarin AB, Walker G. Statistical analysis of industrial-scale roller compactor 'Freund TF-MINI model'. International Journal of Pharmaceutics 2016; 513(1-2: 453-463, https://doi.org/10.1016/j.ijpharm.2016.09.052

27. Sander U, Schönert K. Operational conditions of a screw-feeder-equipped high-pressure roller mill. Powder Technology 1999; 105(1-3): 282-287, https://doi.org/10.1016/S0032-5910(99)00149-7
28. Schenkel G. Schneckenpressen fuer Kunststoffe (Screw presses for plastics). Carl Hanser Verlag, Munich, 1959.
29. Schenkel G. Modelltheorie der Kunststoffextruder (Model theory of plastic extruders). Industrie-Anzeiger, 1972.
30. Semenov YS, Mozharenko NM, Gorupakha VV et al. Effect of the fuel, raw materials, and process conditions on the behavior of temperature change in a blast-furnace lining. Metallurgist 2015; 59: 290–299, https://doi.org/10.1007/s11015-015-0099-0
31. Semenov YS, Shumel'chik EI, Gorupakha VV. Efficient management of the charging of blast furnaces and the application of contemporary means of control over the variable technological conditions. Metallurgist 2018; 61: 950–958, https://doi.org/10.1007/s11015-018-0591-4
32. Shimizu Y, Cundall PA. Three-dimensional DEM simulation of bulk handling screw conveyors. Journal of Engineering Mechanics 2001; 127: 864-872, https://doi.org/10.1061/(ASCE)0733-9399(2001)127:9(864)
33. Vinogradov GA, Katashinskiy VP. Teoriya listovoy prokatki metallicheskikh poroshkov i granul (The theory of sheet rolling of metal powders and granules). Metallurgiya, 1979, 224.
34. Wang C, Wang Z, Friedrich A, Sun CC. Effect of deaeration on processability of poorly flowing powders by roller compaction. International Journal of Pharmaceutics 2022; 621: 121803, https://doi.org/10.1016/j.ijpharm.2022.121803
35. Wennerstrum S. Ten things you need to consider when choosing and installing a roller press system. Powder and Bulk Engineering 2000; February: 37-47. [CrossRef]
36. Zhao R, Guo L, Gao W, Xiao X, Liu Y. Structure optimization design of screw conveyor based on EDEM. 2021 International Conference on Computer Science and Materials Applications. IOP Publishing. Journal of Physics: Conference Series 2200. 2022, 012002 IOP Publishing, https://doi.org/10.1088/1742-6596/2200/1/012002