Model of the pressing and drying system of organic material

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Abstract. The following paper presents a model of a system operating and drying food waste. This paper was written in response to the challenge of reducing food waste, minimizing environmental pollution, decay processes, and exploring the possibility of using said waste. The design of such a system has proven to be innovative, despite still being under construction. Whilst the pressing and drying process itself is not new, the list of process parameters has not previously been used, thus proving innovative in the developed model. High pressure pressing does not only change the geometric form or the physical properties of the material. Such a process also changes the physicochemical properties.

The authors’ previous experience in pressing organic materials is referenced in this work. Basic parameters such as temperature, pressure and process duration have been developed in earlier studies. In the proposed model, the friction against the walls in the compression chamber have been eliminated. This changes the parameters inside the compression chamber and will certainly improve the lifetime of the system. Previous solutions, such as screw presses, or for higher power - piston ones, were not durable and very energy-consuming. The new solution is much more durable and allows for use of higher pressures. Depending on the materials selected for the process, it will be possible to obtain new products that have not been produced before, due to the limitations of the pressing process.

The developed model of pressing and drying organic materials will also allow the further production of ecological fuels from waste materials, like from the waste of the wood industry. It will also allow the use of straw in the production of new building materials. After making the model, there will be a wide scope for further research.

1. Introduction

Pressing organic matter can pose a significant challenge for the designers of pressing systems. The matter is pressed to achieve three main objectives: to reduce the amount of manmade waste, to mitigate potential epidemiological risks, and to produce building and heating materials. In the realm of pressing organic matter, the predominant solutions are screws and hydraulic presses. Belt pressing systems are usually used when pressing large-surface-area materials - also used in the production process of flooring materials and other building panels. The world market for these systems was dominated by two producers that did not extend their research on pressing organic matter.

In this work we present several results obtained by the late Prof. Ireneusz Malujda, from his research on pressing wooden materials [1-8]. The results of his work indicate that the belt press model could be
sought after in constructing future solutions, however, the analysis and further developments of the research were interrupted by the professor’s sudden premature death.

This pressing process is characterized by shaping a nonlinear, elastically fragmented material in the press into a solid geometric form, without the use of external binding agents. The cohesiveness of the compacted material, and its sufficiently durable consolidation, determine the state of plastic flow, which in the thin surface layer is largely affected by the temperature gradient and humidity [1-11].

As a result of friction related to pushing the compacted material through the main chamber and the forming sleeve (in the hydraulic and screw press), the temperature in the subsurface layer increases to a value exceeding 100 °C, which has a positive effect on the plasticization of shredded wood waste. Just like hot rolling wood, during compaction in a conical converging channel, the effectiveness of this process is determined by the plasticization of a thin surface layer of the material under the influence of heat flow under certain humidity conditions. This phenomenon does not occur in a belt press when the surface temperature rise must be caused by the hot belt and the pressure of the belt against the material. The friction of the material of the belt is a resting friction, and it contributes little to the surface temperature increase of the material [1-11].

This characteristic of the plasticizing and thickening process requires the use of appropriate geometric parameters of the pressing system. In addition, it is necessary to associate control of the compaction resistance, the exerted heat, and control of the temperature of the pressing belts in order to stimulate the required state of critical stresses in the structure of the material being formed [1-11].

2. An approximate description of the pressed organic material

Based on the experience gained during the design, construction and implementation of devices for the agglomeration of wood waste was attempted. Firstly, by using an analytical method to formulate constitutive equations describing the process of densification of the medium constituting fragmented material, whilst considering the influence of temperature and humidity changes [1-11].

The limit was defined by the relationship between the constitutive relationships characterizing the process in question. The analysis of plastic flow in a thin layer of the fragmented material was based on the Huber-Mises-Hencky limit strain energy hypothesis, which tells us that the yield stress of the material at uniaxial stretching is taken as the criterion of the material’s limits. The material disintegrating in the compaction processes does not show linear elasticity. Permanent deformations appear directly after the application of a compressive load, equivalent to a change in volume. This is also subject to the influence of the temperature and humidity gradient, and therefore its necessary that modifications were made. Necessary simplifications and assumptions have also been adopted, which is the basis for determining effective parameters [1-11].

An energy model was developed based on the assumption of a fragmented mass of material as a medium with the characteristics of perfect plasticity, flowing through a converging channel, then plasticized and compacted under the conditions of triaxial compression. In order to determine the equivalent yield point, the results of experimental tests were used. The unidirectional compression of shredded wood waste was tested, determining the characteristic (Fig. 1) describing the physical relationship of the actual strain εk with the normal stress σ causing it. This deformation on the abscissa axis completes the σ-εk curve, defining the area of work performed on the path. Based on the adopted model of a perfectly plastic body and the HMH hypothesis, the equality of the actual work determined from the characteristics with the work relating to the OABC parallelogram was assumed (Fig. 1). The area of this parallelogram is equal to the product of its height, which corresponds to the value of the maximum equivalent stress, equal to the yield stress, resulting from the HMH hypothesis and its basis, which is the maximum strain εk determined from the stress-strain material curve [1-11].

The mean and equivalent value of the equivalent stress can be calculated with the following equation.
\[ \sqrt{3} \cdot k_T \cdot \varepsilon_k = \int_0^{\varepsilon_k} \sigma \varepsilon_k \, d\varepsilon, \]

(1)

Where \( \varepsilon_k \) the final strain determined from the actual compaction curve of the tested material, \( \sigma \) is the equivalent stress determined from the diagram during the unidirectional compression test, the expression \( \sqrt{3} \cdot k_T \) denotes the equivalent yield strength according to the Huber-Mises-Hencky hypothesis. \( k_T \) is the mean stress equivalent to the shear yield strength, dependent on the temperature gradient, \( A \) is the area of integration. From such a formulated equation, it is possible to determine the desired \( k_T \) shear strength limit, which is the basis for formulating a mathematical model for the process of plasticization and compaction of shredded wood waste. From this model, the critical strength of the thickening process was determined.

The approach presented is a simplification. However, it should be noted that the fragmented real medium of natural origin is very complex. The mere lack of linearity in every stress-strain relation range is a difficult challenge when describing the optimal plasticity condition based on the available strain hypotheses. Let us also add that in the analyzed processes of plasticization of natural polymers, the influence of temperature and humidity gradients cannot be ignored, which additionally makes problem solving difficult, especially in an analytical way [1-11].

For this reason, we must base the considerations on the determination of the critical force in the process of compacting the fragmented medium on the ideal plasticity model. The critical force of the thickened material can be calculated from the balance of work of external forces and the work of energy dissipation in the area of plasticization and work of overcoming frictional resistance. The results of empirical studies were used to solve the equation describing this force, depending on the geometric parameters of the converging channel and the influence of temperature changes. This applies specifically to the coefficient of internal friction and the friction between the wall forming the material being compacted, as well as the external surface of this material. Determined physical quantities are functions of temperature changes in conditions of certain humidity [1-11].

The dissipation power and the power to overcome friction resistances were determined by knowing the displacement velocities and strain rates of the compacted material. In order to determine these speeds, we formulate the kinematic assumptions of the compaction process of the fragmented material in the channel with geometric parameters, the geometry of which is described below [1-11].

3. The geometry of the bale chamber

The pressing system can be considered to be a channel consisting of two cuboids with adjustable convergence of two opposite walls. The geometric parameters of this channel are shown in Fig. 2. Before starting the execution of the physical model, it is necessary to develop a model dependent on the basic geometric features of the pressing system. The speeds of the pressing belts, the length of the forming chamber \( b \), main \( a \), and the angle of the belts deviation from the chamber axis are the basic parameters influencing the pressing process and surface plasticization. The width of the strips, \( c \), is a parameter that can be used to adjust the system performance. The basic equation for the flow of material through the press system is the known equation conservation of mass [1-11].
\[
\frac{\partial \rho}{\partial t} + \operatorname{div} (\rho \cdot \mathbf{v}) = 0, \tag{2}
\]

where \( \rho \) is the density, \( t \) is the time, \( \operatorname{div} \) is the divergence operator, and \( \mathbf{v} \) is the velocity vector.

When the flow is described in the ortho-Cartesian system, it can be represented as:

\[
v_0 = \begin{bmatrix} v_{0x} \\ v_{0y} \\ v_{0z} \end{bmatrix},
\tag{3}
\]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Geometric and kinematic parameters of the pressing channel: \( D_1 \) - belt distance from the axis at the entrance to the main chamber, \( D_3 \) - belt distance from the axis at the exit of the main chamber, \( a \) - length of the forming channel, \( \alpha \) - half of the convergence angle of the main chamber, \( b \) - length of the main chamber, \( c \) - belt width, \( v_{we} \) - initial velocity of the material at the entrance to the press, \( V_{wy} \) - velocity at the exit from the press.}
\end{figure}

where \( v_{0x}, v_{0y}, v_{0z} \) are components parallel to the axes, \( 0x, 0y, 0z \) then

\[
\operatorname{div} (\mathbf{v}) = \nabla \cdot \mathbf{v} = \frac{\partial}{\partial x} v_{0x} + \frac{\partial}{\partial y} v_{0y} + \frac{\partial}{\partial z} v_{0z}.
\tag{4}
\]

Any function that identifies the mass conservation equation is called a current function. As seen below, the current function equation (4) is any function \( \Psi \):

\[
- \frac{\gamma}{r} \frac{\partial}{\partial x} \Psi = w_{0r}, \quad \frac{\gamma}{r} \frac{\partial}{\partial r} \Psi = w_{0x},
\tag{5}
\]

where \( \gamma \) is any constant.

for \( \Psi = \pi \cdot r^2 \left( \frac{B_x}{D(x_0)} \right)^2 \cdot v_{we} \), we have the following form of expression describing the velocity component \( w_{or} \) in the direction of the axis of the system

\[
w_{or} = \frac{-1}{2 \pi r} \frac{\partial}{\partial x} \left( \pi \cdot r^2 \frac{B_1^2}{D^3(x)} \cdot v_{we} \right).
\tag{6}
\]

After performing the differentiation and transformations, we get:

\[
w_{or} = -\kappa \cdot r \cdot D_1^2 \cdot v_{we} \frac{1}{D^3(x)}.
\tag{7}
\]
Similarly, we will determine the axial velocity component:
\[ w_{oz} = \frac{1}{2\pi} \frac{\partial}{\partial r} \left( \pi \cdot r^2 \frac{D_1^2}{D_3^2(x)} \cdot v_{we} \right). \]  
(8)

By doing differentiation by transforming, we get the axial velocity:
\[ w_{oz} = D_1^2 \cdot v_{we} \cdot \frac{1}{D_3^2(x)}. \]  
(9)

To calculate the dissipated frictional power in the convergent part of the channel, the equation:
\[ w_k = \sqrt{w_{or}^2 + w_{ox}^2} = v_{we} \cdot \frac{D_1^2}{D_3^2(x)} \cdot \sqrt{1 + \kappa^2} \]  
(10)
on the resultant speed of material displacements on the axis of the baling chamber. To determine the dissipation power of the material, we will successively determine the components of the strain velocity in the radial direction \( \dot{\varepsilon}_{or} \)
\[ \dot{\varepsilon}_{or} = \frac{1}{r} w_{or}, \]  
(11)
and in the axial direction \( \dot{\varepsilon}_{ox} \)
\[ \dot{\varepsilon}_{ox} = \frac{1}{r} w_{ox}. \]  
(12)

After performing the differentiation, we get:
\[ \dot{\varepsilon}_{or} = \frac{1}{r} w_{or}, \]  
(13)
\[ \dot{\varepsilon}_{ox} = -2 \frac{1}{r} w_{ox}. \]  
(14)

The length of the strain vector at any point of the material to be plasticized is therefore equal:
\[ |\dot{\varepsilon}| = \sqrt{\dot{\varepsilon}_{or}^2 + \dot{\varepsilon}_{ox}^2} = \sqrt{\left(\frac{1}{r} w_{or}\right)^2 + \left(-2 \frac{1}{r} w_{or}\right)^2} = \frac{\sqrt{5}}{r} |w_{or}| = \sqrt{5} \cdot D_1^2 \cdot v_{we} \cdot \kappa \cdot \frac{1}{D_3^2(x)}. \]  
(15)

The successively determined velocities of displacements and deformations and their resultants in the radial and axial directions make it possible to determine the critical value of the force causing the state of plastic flow of the particulate material in a circular conical channel [1-11].

**4. Critical strength of plasticization of the shredded material**

The value of the critical force (also known as the plasticizing force) \( F \) is of interest to us. It is capable of compacting the fragmented material in the pressing channel, which is determined from the power balance expressed by the equation that the external power \( P_z \) is the sum of the energy dissipation power in the area of plasticization \( P_d \) and the power to overcome frictional resistance \( P_\mu \) [1-11]
\[ P_z = F \cdot v_{we}, \quad P_z = P_d + P_\mu, \]  
(16)
the frictional power \( P_\mu \) is equal to the sum of the frictional power in the forming chamber \( P_{\mu s} \) and the main chamber \( P_{\mu m} \).

For the forming chamber, the power of plastic deformation dissipation will be written as:
\[ P_d = \frac{\int_{x=0}^{b} \int_{\theta=0}^{\theta_{(+)}} dx \int_{r=0}^{R(z)} 2r \sqrt{3} \cdot k_r |\dot{\varepsilon}| d\theta}; \]  
(17)
where \( \sqrt{3} \cdot k_T \) is the equivalent yield point according to the Huber-Mises-Hencky hypothesis, and \( k_T \) is the mean stress equivalent to the shear yield point, depending on the temperature gradient. The integration in the equation (17) leads to describing the power used for dissipation of plastic strains in the forming channel, with the following final form:

\[
P_d = \sqrt{15} \cdot k_T \cdot \nu_{we} D_1^2 \ln \frac{D_1}{D_3}
\]

In the belt press, the heat dissipated due to the friction of the surface of the plasticized material against the surface of the forming chamber can be ignored, the power \( P_{\mu} \), which is an important element of the process, carried out in other types of presses. The heat caused by friction in the belt press must be compensated by the heat supplied to the belts in the pressing process, and the power for this process will be denoted by \( P_B \) [1-11].

Balance of power, comparing the sum of dissipation power \( P_{\mu} \) and frictional power \( P_B \) with the power of external forces, we write:

\[
F \cdot \nu_{we} = \sqrt{15} \cdot k_T \cdot \nu_{we} D_1^2 \ln \frac{D_1}{D_3} + P_B
\]

By dividing both sides of this equation by \( \nu_{we} \), we obtain the final formula for the value of the plasticizing force of the shredded material in the compacting channel:

\[
F = \sqrt{15} \cdot k_T \cdot D_1^2 \ln \frac{D_1}{D_3} + \frac{P_B}{\nu_{we}}
\]

However, the power secured to supply heat to the \( P_B \) belts can be determined experimentally, starting from the values determined for conventional presses, to overcome the friction forces \( P_{\mu} \):

\[
P_B = P_{\mu} = 2 \pi \cdot \mu_T \cdot k \cdot \nu_{we} \cdot D_1^2 \cdot \left( \frac{D_1}{D_3} \cdot \sqrt{1 + \frac{a}{D_3 \cos \alpha}} - \ln \frac{D_1}{D_3} + \frac{a}{D_3} \right)
\]

In the case of the belt press model, it is important to properly select the diameter of the pressure rollers and the possible displacement of the upper shaft in relation to the lower one. The calculated pressure forces determine the thickness and material of the belts, which in turn determines the diameter of the shafts. A thick and stiff belt requires a shaft with a diameter that will not cause excessive bending stresses in the belt [1-11].

5. Model of a belt press for pressing natural polymers

The plasticization process of natural materials with such complex properties as, for example, straw, wood, or bread, has not been described theoretically in a non-linear way thus far [14-16]. There is a lack of a mathematical model meeting the engineering needs, the structure of which would be the complex engineering constants, characteristic of natural polymers [7-13]. Such was attempted on a sample of wood subjected to hot rolling (Fig. 3). Analytical studies were carried out on the formulation of constitutive compounds of natural materials with specific properties in the field of plasticity theory, taking into account plastic compressibility and the influence of temperature and humidity gradient [1-4].
Figure 3. Directions of orthotropy of the plasticized material and basic parameters geometric, where: F – cylinder pressure force on the material surface, s – cylinder contact segment with plasticized material, h₁ – initial thickness, h₂ – thickness of the layer after plasticization, l – width of the plasticized element [1].

When modeling the densification and plasticization processes, the ultimate focus is the limit effort, the limit load capacity corresponding to the lower, and the static estimate of the load capacity of the loaded material layer. Hence, the main goal is to determine the critical force of plasticization from the formulated mathematical model. Its value has a decisive influence on the effectiveness of the considered process [17-19]. It is also necessary to solve boundary problems and model verification (Fig. 4).

Figure 4. Model of the pressing channel of the belt press.

In order to build a correct model, all the related issues can be treated as process identification in the material. Therefore, a thorough analysis of those elements that make up the model structure that determine the satisfactory result of its solution should be made. In the case of the materials considered in this paper, they are complex thermomechanical properties, porosity and process parameters, in particular the critical force F depending on the temperature gradient and the duration of the process. It should be mentioned that the above considerations only concern the effort of incompressible media, e.g., taking into account only the second invariant of the stress deviator. Wood is a highly porous material; therefore, the first stress tensor invariant also has an influence on its limit strength. This influence must be considered in the final form of the yield condition [13]. Plasticization of anisotropic and porous materials, such as wood, requires the development of a condition that takes into account the change in volume and strength properties depending on the orientation of the fibers. Hence, the axis directions of the adopted reference system were related (Fig. 5.3), with orthotropic orientations of the L, T, R fibers. Taking this into account, the Huber plasticity condition was used, generalized by Mises due to orthotropy, which, written in the simpler Voigt notation, has the following form [1-11]:

\[ A_{ij} \sigma_i \sigma_j = 1 \]  

(22)

where \( \sigma_i \) is the stress tensor components, \( \sigma_j \) is the stress deviator components, and \( A_{ij} \) is the tensor of anisotropy modules

Scalar functions: porosity, temperature and humidity were introduced to the plasticity condition formulated in this way after its generalization due to anisotropy. In further versions, a physical model of a rigid-plastic medium without reinforcement was adopted [1-13].

Therefore, for the general plasticity condition (22), expressing the plasticity criterion for a material with anisotropic properties and porosity, considering the influence of the temperature gradient and humidity, we will generally write as a function describing the plasticity surface, in the following form:

\[ F(\sigma, f_v, T, W) = 0 \]  

(23)
where $\sigma$ is a stress tensor and scalar functions: porosity $f_v$, temperature $T$ and humidity $w$. The structure of the plasticity condition formulated in this way is made up of interrelated physical quantities, none of which can be omitted due to the efficiency of the wood top layer refining process. Wood has a porosity that affects its yield point. This influence was taken into account in the formulated mathematical model by introducing the following porosity scalar functions [1-11]:

$$A = \frac{f_v}{1 - f_v}, \quad B = 1 - f_v.$$  \hspace{1cm} (24)

Note that they meet the following border crossings:

- if $f_v \rightarrow 0$, $A \rightarrow 0$, to $B \rightarrow 1$,
- if $f_v \rightarrow 1$, $A \rightarrow \infty$, to $B \rightarrow 0$,

which reduces condition (24) to condition HMH.

By introducing the porosity functions into the equation, we obtain the relationship in the form:

$$A(\sigma_1 + \sigma_2) + (\sigma_1 - \sigma_2)^2 = BY^2,$$  \hspace{1cm} (25)

where $\sigma_1$ and $\sigma_2$ principal stresses in the directions of fibres orientation 1-2.

In the plasticity condition (25), the complex state of stress was compared with the effort expressed as the non-zero main stress, which was determined, experimentally, as a function of temperature and humidity changes during the uniaxial compression test Y1. In the critical state of stress, this stress will assume a constant value on the limit of wood strength exhaustion. It was assumed that the quantity determining the critical stress of the natural polymer – e.g. the one caused by the action of the destructive force - is the yield stress during the compression test (it is assumed that for materials such as those considered in the paper, it corresponds to the limit of proportionality and the limit of elasticity). This strength is the basis for assessing the technical value of composite materials, which also include wood, and depends on the temperature and humidity values and the anatomical direction to which the load is applied [1-6].

During the process of rolling a thin layer of wood in the first pressure phase of the roller, permanent deformations arise without a significant influence of temperature. However, they are necessary, to such an extent, to determine the time of mutual contact of the roller with the wood surface, necessary for overheating its thin layer, to a temperature oscillating, depending on the type of wood, around 120 °C. This process, as shown by experiments, takes place in a very short time, e.g., approx. 0.04 to 0.1 s. During this time, the wood layer overheats into its structure to a depth of approx. 0.1-0.12 mm, which is the basis for its refinement [1-12].

The aforementioned process can, therefore, be divided into two stages. The first concerns permanent deformations as a result of exceeding the limit of proportionality, related to the compaction of the wood structure. The second stage makes the overheated surface layer smooth and consolidates its structure under the influence of heat flow and the action of the decreasing pressure of the roller on the material surface. The decrease in this force is the result of the decreasing strength of the wood due to the temperature increase in the structure of the refined wood.

By adopting the aforementioned parameters as a starting point for the design of belt presses, it is possible to start calculating the geometric features of the physical model (Fig. 5). There are only a few manufacturers of steel belts in the world, and the four largest ones use steel supplied from Japan. Assuming the properties of steel are invariable, they can only test finished products. Several of them have prepared small test lines, on which you can try to iron various materials. The dimensions of these lines significantly exceed the dimensions of the sought model, and you can try to examine the parameters of the pressing processes of various materials.

These systems are prepared for pressing plastics and other polymers, for which the pressing parameters are well described, and the manufacturer looks for the parameters influencing the physical properties of the material.
6. Conclusion
Solving complex engineering problems related to pressing and surface plasticization of the top layer of organic materials by belt pressing and agglomeration of its fragmented waste requires the recognition of the boundary stress states, which correspond to the specific strength properties of the material. In modeling both processes, plasticization and densification of comminuted organic materials, the material strength limit at which its plastic flow begins is of fundamental importance. Evidence shows that, even though these are two different technological processes, they relate to the same material as the components that make up the structure and its properties. In addition, the physical quantity sought in both processes, determining their energy consumption and efficiency, is the actual force dependent on the temperature and humidity gradient, as well as the geometry and parameters of the surface of the tool that shapes it. It is the starting point for the design and implementation of the physical model of the belt press.

Plasticity conditions are defined by constituent relations of the state of stresses and strains, as well as material constants at the material stress limit, which corresponds to the appearance of plastic strains. The research conducted was based on the basic assumption of the theory of plasticity, which says that plastic deformations can only be the result of the occurrence of shear deformations. It follows the reasoning that, depending on the way of defining the relationships between the stress deviator and the strain deviator, according to the specific strain criterion and the applied strain hypothesis, different plasticity conditions can be formulated. The paper presents the results of considerations, based on the theory of plasticity, aimed at formulating, on a macroscopic scale, a model of a continuous medium of a porous natural polymer with anisotropic properties.

The structure of the model considers experimentally determined material functions, which reveal the specific features of natural polymers such as wood and its shredded waste. This applies to different strength and plastic compressibility, depending on the direction of the fiber orientation and the heat and humidity flow.

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