Framework to evaluate efficiency of peat processing using roller-disc grinding machines

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Abstract. The article analyses factors affecting the quality of products manufactured on the basis of peat raw materials. The method for estimating the degree of peat processing by means of the roller-disk mechanism is presented taking into account the assumption of the continuity condition and the unchanged volume of the passing raw materials. This will further determine the energy cost for manufacturing peat products with the use of similar devices.

1. Introduction
In the production of high-quality peat products from excavated peat, it is necessary to take into account a wide range of factors that can be conditionally combined into the following groups: properties of excavated raw materials, meteorological conditions, parameters of machines and mechanisms used in the extraction and processing of raw materials [1, 2, 3]. In the first group, the degree of peat processing can be identified as a determining factor, significantly affecting the technological processes of drying, energy costs and, ultimately, the quality of the products.

2. Methods
In the practice of field manufacture of peat products in the form of different in shape and size pieces, mechanisms on the basis of screw extruders are applied most widely due to high processing ability, simple design and freedom to choose a moulding arietage. However, in many cases, screw moulding machines are inefficient in terms of energy indicators, especially in regard to the specific energy costs per ton of products. Therefore, attempts to create other more efficient and productive processing-moulding devices continue aiming at manufacturing field raw material products with the pre-defined particle-size distribution [4, 5]. The use of roller-disc grinders is one of the promising directions for creating such devices. Its principle of action allows combining the separation of peat raw material and primary processing for the production of various peat-based goods [6, 7]. To determine the degree of peat processing in a roller-disk device, we determine its relative deformations when passing through the space between two adjacent rolls with disks connected to the rolls through the hubs. Processing in such mechanism is carried out due to shear strains, which arise as a result of sliding layers of peat relative to each other, and also due to crushing deformation when narrowing in the space between two adjacent rolls. In determining the relative strains that arise in this case, we assume that the conditions of continuity and invariability of the volume are satisfied.

Shear deformations due to the difference in the velocities of peat layers in a plane perpendicular to the axes of the rolls are of complex nature due to mismatching motion directions of peat particles
contacting the lateral surfaces of disks with the velocities of the points of these surfaces. We divide the area in which peat is divided into several parts so as to calculate the mean values of processing degree in them [8]. Let us first consider the area (Figure 1) between the lateral surfaces of two disks belonging to adjacent rolls.

![Figure 1. Determining the space between the peat processing discs](image)

3. Results
With identical rotation speeds of rolls and geometrical sizes of disks, the speed field of lateral surface points of disks is symmetric concerning geometrical axes of the disk intersection figure. This figure is made of two combined chords that are equal by segments with central corners 2α.

Let us determine the volume of material passing through this figure:

\[ Q_d = S_d \cdot v, \]

(1)

where \( S_d \) is for the cross-sectional area of the flow of material passing between the discs; \( v \) is for speed of material in this section, m/s.

Cross-sectional disc area \( S_d \):

\[ S_d = b(h_d - b_d), \]

(2)

where \( b \) is for width of a passage section, m; \( h_d \) is for step of setting the disks on the roller, m; \( b_d \) is for disk thickness, m; \( h_r \) is for roller diameter, m.

Section width of material flow between discs varies from zero to the maximum value \( b_{\text{max}} \) and back to zero. The current value of the section width (Figure 2):

\[ b = (2 \cdot r_d - h_r) - 2 \int_0^\alpha db, \]

(3)

where \( db \) is for the differential of the width of the section expressed as \( \alpha \) angle, measured from a plane containing roller axes:

\[ db = r \cdot \sin \alpha \cdot d\alpha. \]

(4)

Integrating and determining the integration constant at \( \alpha = 0 \), the result is:
\[ b = \left(2 \cdot r_d - h_r\right) - 2 \cdot r_d \left(1 - \cos \alpha\right), \quad \text{or} \quad b = 2 \cdot r_d \cdot \cos \alpha - h_r. \]  
\[ (5) \]

**Figure 2.** A settlement scheme of determination of relative peat deformations during passage through the roller-disk surface [10]

So:

\[ S_d = \left( h_d - b_d \right) \cdot \left(2 \cdot r_d \cdot \cos \alpha - h_r\right), \]
\[ (6) \]

\[ Q_d = \left( h_d - b_d \right) \cdot \left(2 \cdot r_d \cdot \cos \alpha - h_r\right) \cdot v. \]
\[ (7) \]

In determining the material velocity in the corresponding sections, we assume that it increases from the initial value in the largest section to the section of the smallest width, in accordance with condition \( s \cdot v = \text{const} \).

the initial sectional area is \( s_0 = a \cdot b \). Further, it decreases according to the law:

\[ s = s_0 - 2 \cdot z_r \cdot z_d \cdot b_d \cdot r_d \cdot \cos \alpha \quad \text{when} \quad r_d \cdot \sin \alpha \geq r_{ht}; \]
\[ (8) \]

\[ s = s_0 - 2 \cdot z_r \cdot z_d \cdot b_d \cdot r_d \cdot \cos \alpha - 2 \cdot z_r \cdot z_d \cdot b_{ht} \cdot r_{ht} \cdot \cos \alpha \quad \text{when} \quad r_{ht} \cdot \sin \alpha \geq r_d; \]
\[ (8) \]

where \( b_d, b_{ht} \) are for disc and hub thickness, m; \( r_d, r_{ht}, r_r \) are for disc, hub and roller diameters, m; \( z_r \) is for number of rollers; \( z_d \) is for number of disks on the roller.

With constant performance \( Q \), the average material flow rate is \( v = Q/S \). Through this speed value, we determine the time needed for the processed material to pass the space between the lateral surfaces of the disks:

\[ t = l/v, \]
\[ (9) \]

where \( l \) is for the length of the material path as it passes between the lateral surfaces of the disks. This distance depends on the position of the part of the material flow relative to the rollers:

\[ l = 2 \cdot r_d \cdot \sin \alpha_k, \]
\[ (10) \]

where \( 0 \leq \alpha \leq \alpha_k \) is for half of the current contact angle of the discs.

The processing degree also depends on this distance. Determining the elementary degree of processing through the speed of adjacent layers of peat:
\[ d\lambda_1 = \frac{1}{2} \cdot \frac{v_2 - v_1}{h_d - b_d} \cdot dt, \]  

where \( v_2, v_1 \) are the speed of peat when it touches the lateral surfaces of the discs.

\[ d\lambda_1 = \frac{1}{2} \cdot \frac{v_2 - v_1}{h_d - b_d} \cdot \frac{dl}{v} = \frac{v_2 - v_1}{h_d - b_d} \cdot \frac{r_d \cdot \cos \alpha}{v} \cdot d\alpha. \]  

Thus:

\[ \lambda_1 = \int_{-\alpha}^{\alpha} \frac{v_2 - v_1}{h_d - b_d} \cdot \frac{r_d \cdot \cos \alpha}{v} \cdot d\alpha = \frac{r_d}{2} \cdot \frac{(h_d - b_d)}{v} \cdot \int_{-\alpha}^{\alpha} (v_2 - v_1) \cdot \cos \alpha \cdot d\alpha. \]  

Productivity through a part of the section where the degree of processing reaches \( \lambda_1 \):

\[ dQ_1 = v \cdot dS, \]  

where \( dS_1 = (h_d - b_d) \cdot r_d \cdot \cos \alpha \cdot d\alpha \).

So:

\[ Q_1 = v \cdot r_d \cdot \cos \alpha. \]  

We now determine the average degree of processing of material in the space between the disks:

\[ \lambda_{1e} = \frac{\int \lambda_1 dQ_1}{Q_{10}} = \frac{2 \cdot r_d^2}{Q \cdot (h_d - b_d)} \cdot \int_{0}^{\alpha} (v_2 - v_1) \cdot \cos \alpha \cdot d\alpha = \frac{r_d^2}{Q \cdot (h_d - b_d)} \cdot \sin \alpha_{\epsilon}^2, \]  

where

\[ \sin \alpha_{\epsilon} = \sqrt{\frac{r_d^2 - \frac{1}{4} h_r^2}{r_d}}. \]  

If we determine the average value of the difference \( v_2 - v_1 \) peat velocities near the lateral surfaces of disks, then we finally have:

\[ \lambda_{1e} = \frac{2 \cdot r_d^2}{Q \cdot (h_d - b_d)} \left( \int_{0}^{\alpha} \cos \alpha \cdot d\alpha \right)^2 = \frac{2 \cdot r_d^2 \cdot (v_2 - v_1)}{Q \cdot (h_d - b_d)} \cdot \sin \alpha_{\epsilon}^2, \]  

where

\[ v_2 = v_{2d} - v_{id}; \quad v_1 = v_{id} + v_{rd}. \]
where $v_2'$ is for peat velocity in places where it touches the lateral surfaces of the second disk, m/s; $v_{2d}$ is for the speed of a point of a disk in contact with a peat having a velocity $v_2'$; $v_1'$, $v_{1d}$ are the same for the first disk; $v_{sl}$ is for the speed of peat sliding relative to the lateral surfaces of the discs:

$$v_{2d} = \omega \cdot r_2 \cdot \cos \alpha_2; \quad v_{1d} = \omega \cdot r_1 \cdot \cos \alpha_1;$$

$$v_2' = \omega \cdot r_2 \cdot \cos \alpha_2 - v_{sl}; \quad v_1' = \omega \cdot r_1 \cdot \cos \alpha_1 + v_{sl},$$

where $r_1$, $r_2$ are for current contact radii.

Average speeds $v_2'$ and $v_1'$ are defined by averaging the common contact area of the lateral surfaces and peat:

$$v_2 = \frac{\int r_2' \omega \cdot r_2 \cdot \cos \alpha_2 \cdot d\alpha \cdot d\omega - \int r_{2d} \omega \cdot r_2 \cdot d\alpha \cdot dr}{r_2^2 (2 \cdot \alpha_k - \sin 2 \alpha_k)};$$

$$v_1 = \frac{\int r_1' \omega \cdot r_1 \cdot \cos \alpha_1 \cdot d\alpha \cdot d\omega - \int r_{1d} \omega \cdot r_1 \cdot d\alpha \cdot dr}{r_1^2 (2 \cdot \alpha_k - \sin 2 \alpha_k)},$$

where $r_1'$ and $r_2'$ are for the boundaries of the common contact area.

Having determined the limits of integration $r_2' = r_d$, $r_1' = r_d - h / 2$ and performing the integration taking into account that $v_{sl} = const$, the result is:

$$v_2 = \frac{\omega \cdot \left(r_2^3 - \frac{h^3}{8}\right) \cdot 2 \cdot \sin \alpha_k}{3 \cdot r_2^3 \cdot (2 \cdot \alpha_k - \sin 2 \alpha_k)} - v_{sl}.'$$

To calculate $v_2'$ and $v_1'$ we can use formulas:

$$v_2 = \frac{2}{3} \omega \cdot r_2 \cdot \sin \alpha_k \cdot \sin \alpha_k - v_{sl},$$

$$v_1 = \frac{2}{3} \omega \cdot r_1 \cdot \sin \alpha_k + v_{sl}.'$$

So:

$$v_2 - v_1 = \frac{4}{3} \omega \cdot r_2 \cdot \frac{\sin \alpha_k}{2 \cdot \alpha_k - \sin 2 \alpha_k} - 2 \cdot v_{sl},$$

and

$$\lambda_{ec} = \frac{8}{3} \omega \cdot r_d^3 \cdot \frac{\sin^3 \alpha_k}{Q \cdot (h_d - b_d) \cdot (2 \cdot \alpha_k - \sin 2 \alpha_k)} - \frac{4}{3} \frac{v_{sl} \cdot r_d^2 \cdot \sin^2 \alpha_k}{Q \cdot (h_d - b_d)}. $$

Shift deformations due to a change in the cross-section of the flow of material passing through the rolls are determined from the condition of its continuity and the invariance of the size of the cross section.

$$dh_r = r_r \cdot d\beta \cdot \cos \beta;$$
\[ \text{de}_1 = r \cdot d\beta \cdot \cos \beta. \] (28)

These conditions give the following relationships between the relative deformations along three mutually perpendicular axes:

\[ \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} = 0, \] (29)

where \( \varepsilon_{11} = \frac{d_1}{h_r} \) and \( \varepsilon_{22} = 0 \).

Thus:

\[ \varepsilon_{33} = -\varepsilon_{11}, \quad \text{and} \quad d\lambda_2 = \sqrt{2} \cdot d\varepsilon_{11} = \sqrt{2} \cdot \varepsilon_{11}, \quad \text{and} \quad \lambda_2 = \frac{v_2}{\sqrt{2}} \cdot \frac{d_r}{h_r}. \] (30)

Shear deformations along cylindrical surfaces of rollers, hubs and discs are the third component of the strain intensity tensor. These deformations propagate in a small part of the material flow near these surfaces. To calculate the strain intensity, we use the formula:

\[ d\varepsilon_{31} = \frac{v - v_0}{\delta} \cdot dt, \] (31)

where \( \delta \) is the speed of material flow, m/s; \( \delta \) is for thickness of the wall part of the stream, m.

As before, \( dt = dl/v \); so:

\[ d\varepsilon_{31} = \frac{v - v_0}{\delta} \cdot dl. \] (32)

Since \( dl = r \cdot d\alpha \), where \( \alpha \) is for the contact angle of the rotors with the material, rad, then:

\[ d\varepsilon_{33} = \frac{v - v_0}{\delta} \cdot r \cdot d\alpha_i, \] (33)

where \( i = 1, 2, 3 \) are for the number of the element interacting with peat (1 is for disc; 2 is for hub; 3 is for roller); \( \alpha_{ci} \) is for the contact angle of the cylindrical surface of the corresponding element with peat, rad.

If we consider the space between two rollers, then all contact angles of the cylindrical surfaces of the corresponding elements should be considered equal. So:

\[ \varepsilon_{31d} = \varepsilon_{31c} = \varepsilon_{31r} = \frac{v - v_0}{\delta} \cdot r \cdot \alpha_{ci}, \] (34)

The total relative deformation in the wall layer:

\[ \varepsilon_{31} = \varepsilon_{31d} + \varepsilon_{31c} + \varepsilon_{31r} = \frac{v - v_0}{\delta} \cdot \alpha_{ci} \cdot \left( \frac{d_r + r_c + r_r}{h_r} \right). \] (35)

The degree of processing in this layer:

\[ \lambda_3 = \sqrt{2} \cdot \varepsilon_{31} = \frac{v - v_0}{\delta} \cdot \alpha_{ci} \cdot \sqrt{2} \cdot \left( \frac{d_r + r_c + r_r}{h_r} \right). \] (36)

Expressing performance through this layer:

\[ Q_b = \frac{v + v_0}{2} \cdot \left[ z_d \cdot \delta_d \cdot \delta + z_d \cdot \delta \cdot \delta + z_r \cdot \delta \cdot \delta + \left( b - z_d \cdot \delta_d - z_d \cdot \delta \right) \right] = \] (37)

\[ = \frac{v + v_0}{2} \cdot z_d \cdot \delta \cdot \left[ z_d \cdot \delta_d + z_d \cdot \delta_d + z_d \cdot \delta + \left( b - z_d \cdot \delta_d - z_d \cdot \delta \right) \right]. \]

Now we can determine the average value of the degree of processing of peat as it passes through the processing roller-disc mechanism:
\[ \lambda_c = \frac{\lambda_1 \cdot Q_1 + \lambda_2 \cdot Q_2 + \lambda_3 \cdot Q_3}{Q} \]  

(38)

4. Conclusion
The theoretical analysis of the parameters of a roller-disc recycling device is performed with the assumption of constancy of characteristics of processed peat raw materials, the continuity of the material flow through the processing surface and the equality of the contact angle at all surfaces [11, 12].

The presented technique can be applied to the calculation of the processing degree of peat raw materials on devices equipped with a roller-disk screening surface, which will further determine the energy cost for manufacturing peat products with the use of similar machines.

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