Substantiation of the expediency of using the effect of electric fields on the process of moisture removal from porous waste structures

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Abstract. During this study, information was collected and analyzed in the perspective of producing an electroosmotic installation, in other words, a converter of colloidal polydisperse systems into capillary-porous by electroosmotic dehydration in order to reduce the residual moisture of sludge from sewage and the pulp and paper industry. Exponents were taken as models expressing the mass of the pulp in function of the drying time and the value of electric current. According to the coefficients of determination, the models were consistent with the initial experimental data. Exponential models were used to further optimize the process of converting colloidal polydisperse systems into capillary-porous.

1. Introduction

The purpose of this study is to collect and analyze information in the perspective of producing an electroosmotic installation, in other words, a converter of colloidal polydisperse systems into capillary-porous by electroosmotic dehydration in order to reduce the residual moisture of sludge from sewage and the pulp and paper industry. The possibility of producing insulation materials using dehydrated osprey as a raw material was analyzed in order to increase the productivity of technological innovations in the environmental safety field of industrial enterprises [1]. The relevance of the study is confirmed by the urgent need for innovative approaches to solve the environmental issue by modern industrial enterprises. In addition, high quality indicators of imported products create a competitive environment for developing local enterprises. A solution to this situation may be the active introduction of modern technologies into the local production.

During various technological processes a significant amount of wet waste and residues is formed. In the pulp and paper industry (PPI), a large number of osprey is formed. Pulp is a multi-tonnage, environmentally friendly treatment plant waste of the paper industry, which is a composite material containing environmentally friendly compounds of the raw material mixture for paper making [2].

2. Methods

The wet pulp is initially presented in a colloid polydisperse system. However, with a decrease in moisture content, wet waste takes on the typical properties of capillary-porous materials. For further energy-efficient disposal of wet waste, the possibility of producing a model for converting colloidal polydisperse systems into capillary-porous, necessary for pressing and electrodynamic separation of moisture from waste structures is considered.
The principle of the model for converting colloidal polydisperse systems into capillary-porous for the purpose of further electroosmotic dehydration is to achieve the maximum energy-efficient effect from the dehydration process. Figure 1 shows schematically an optimized device of an electroosmotic installation for the dehydration process of waste paper production, where: 1 - body made of insulating material; 2 - mobile electrode; 3 - stationary electrode with perforation; 4 - screw cap, 5 - creating (regulating) the initial pressure (torque wrench) of the compression of the osprey (6). Electrodes (2) and (3) are supplied with wires, (7) and (8) with an electrical voltage (electric current) that provides the necessary electric field strength, causing particle velocity variation, 9 - perforation in the housing along the entire perimeter, providing additional convection dehydration after the completion of the electroosmosis process when the electrode is raised. (2), 10 is an external casing angle regulator that provides convection dehydration of the lower layers of the mass after the electroosmosis process is completed, 11- isolation pallet for collecting the separated moisture.

![Figure 1. Laboratory electroosmotic installation](image)

This technical solution allows the most energy-efficient electroosmotic dewatering process if compared with the already existent technology, since the variation of direct and alternative current (for example 8, 16, 24 V) at an output current of the voltage source of 20A. This produces a Joule heat effect. The released heat energy in the process of dehydration is given in Table 1, contributing to dehydration without additional energy costs [3].

| $t^*,h$ | 0   | 0,08 | 0,16 | 0,25 | 0,33 | 0,42 |
|---------|-----|------|------|------|------|------|
| $w_0,W$ | 0   | 3,919| 6,9623| 9,5808| 11,3588| 12,888|
| $t^*,h$ | 0.5  | 0.58 | 0.66 | 0.75 | 0.83 | 0.91 |
| $w_0,W$ | 13,9274| 14,7340| 15,360| 15,8993| 16,265| 16,5494| 16,7939 |

Thus, the technical solution contributes to the additional separation of moisture under the action of gravity and partial convection drying, thanks to the perforated cathode and the housing of the installation. To increase the dehydration and increase the energy efficiency of the system, the structure of the pulp solid phase can be modified. It is possible to achieve this in several ways: by coagulation of the pulp with various chemical reagents, by flocculation, by introducing certain filler materials, by thermal conditioning (sudden changes in temperature) — by freezing (or thawing), as well as by magnetic or electromagnetic treatment. As a result, a significant enlargement of the particles of the pulp occurs and the average surface area of the dispersed phase and the dispersion medium decreases. The average surface energy decreases and the forces of moisture binding to solid particles significantly weakens. The
redistribution of types (forms) of moisture is actively carried out, and the content of “free water” increases due to a decrease in the total amount of “the bound water”. Moreover, all the above methods are quite costly [4].

The research results show that the method of electroosmosis can remove a significant amount of liquid from the volume of pulp without resorting to the use of coagulants and at the same time the energy costs can be less than when using thermal drying. It was established, as a result of a series of experiments, that the method of electroosmosis removes moisture from wet pulp quite effectively.

According to the analysis, the electrokinetic phenomenon of moisture transfer through the pore space of capillary-porous media, caused by an external electric field imposed on the diaphragm, was one of the first to be observed by Professor F.F. Reuss. The flight, which he called "water expelling force." Subsequently, this phenomenon called "electroosmosis" refers to the movement of fluid relative to the solid skeleton of a porous material under the action of an electric field in the direction determined by the sign of the electrokinetic potential. [5] When an electroosmosis process is carried out, the divergence of the phase charges leads to the displacement of moving counter ions in a constant electric field together with the liquid phase to the corresponding pole of the current source. The electroosmotic transfer of fluid through the pore space of a capillary-porous body is determined by the electrokinetic potential and the structure of the electrical double layer at the interface of the phase.

The linear electroosmotic velocity of the fluid is determined by the formula:

$$V_l = V_g + \frac{I \xi \varepsilon}{4\pi \eta \kappa r^2}, \quad (1)$$

and the volumetric electroosmotic velocity of the fluid will be equal to:

$$V_o = \frac{I \xi \varepsilon}{4\pi \eta \kappa}, \quad (2)$$

where

- $V_l$ – the electroosmotic linear speed;
- $V_g$ – hydrostatic speed;
- $V_o$ – electroosmotic volumetric speed;
- $I$ – current intensity;
- $\xi$ – dielectric constant;
- $\varepsilon$ – the electrical conductivity of the fluid;
- $\eta$ – fluid viscosity;
- $r$ – radius of the capillary;
- $\kappa$ – electrokinetic potential. [6]

The earliest known model of the structure of a double electric layer, which allowed to explain not only the existence of electrokinetic phenomena, but also to quantify the value of the capacitance of a double electric layer, was proposed by Helmholtz [7].

Applying innovative technologies such as paper waste dehydration (pulp), the end result is not only the production of unique products (insulation), but also the achievement of environmental and social impact (more than 2000 m3 of waste does not enter the soil factories with average power), while reducing the negative impact on the human health, due to the decay and decomposition of waste [8].

The results of the experiments on the study of electroosmosis obtained in the developed installation, are presented in Table. 2. The reflect of the process of reducing mass $m$ (Figure 2) and the process of reducing current $i$ (Figure 3).

| $t_j$ | 0 | 0,16 | 0,33 | 0,5 | 0,66 | 0,83 | 1 |
|-------|---|------|------|----|-----|-----|---|
| $m_j$ | 70 | 48 | 38 | 35 | 32 | 29 | 27 |
| $ij$  | 2,5 | 1,63 | 1,21 | 0,8 | 0,53 | 0,31 | 0,09 |
Figure 2. Experimental graph of mass loss in the process of electroosmotic dehydration of the pulp

Figure 3. Experimental graph of current reduction in the process of dehydration (drying)

From these data, it follows that as models mass expression of the pulp, in function of the drying time and the value of electric current (under certain initial conditions), we can take the exponents: to change the mass of the pulp:

\[ m(t_j) = m_0 \cdot e^{\frac{t_j}{\tau_m}}, \]  

(3)

where \( m_0 \) - initial value of the mass of the osprey, loaded into the installation; 
\( \tau_m \) - time constant of weight reduction 
\( t_j \) - moment of mass control \( t_j \in \{0; \tau_1; \ldots \tau_m\} \), 
And to change the current:

\[ i(t_j) = I_0 \cdot e^{\frac{t_j}{\tau_i}}, \]  

(4)

where \( I_0 \) - initial value of the electric current flowing through the scopa; 
\( \tau_i \) - time constant of the process of reducing the current when on the plates (electrodes) of the installation.

while \( U = const \) on the plates (electrodes) of the installation.

Observations have shown that, when the process of controlling the effect of electroosmosis, started, the pulp dries to a certain extent by the convective method. This loss was excluded during the processing of experimental data and in the further study of electroosmosis. This made it possible to estimate more accurately the relationship between the electric current flowing through the pulp and the decrease in its mass caused by electroosmosis.

To avoid the influence of oscillations of the initial mass of the pulp that occurs when the installation is loaded, we move from the subject scales of mass \( m(t) \) and current \( i(t) \) to universal ones by following the formulas
The data presented in table 9 are in units of universal scales.

Table 3. Experimental data on the study of electroosmosis in universal scales.

| \( j_0 \) | 0 | 0,16 | 0,33 | 0,5 | 0,66 | 0,83 | 1 |
| --- | --- | --- | --- | --- | --- | --- | --- |
| \( \delta_m(t_j) \) | 1 | 0,69 | 0,54 | 0,5 | 0,46 | 0,41 | 0,39 |
| \( \delta_i(t_j) \) | 1 | 0,65 | 0,48 | 0,32 | 0,12 | 0,09 | 0,03 |

The main parameters in models (5) and (6) are time constants. For their estimation, the model is subjected to linearization by logarithmization.

\[
\ln \delta_m(t_j) \cdot \tau_m = -t_j; \tag{7}
\]

\[
\ln \delta_i(t_j) \cdot \tau_i = -t_j; \tag{8}
\]

and to the known rules of the method of least squares (OLS).

Taking into account (7) and (8) the sums of squares for \( S_m^2 \) and \( S_i^2 \) can be written as:

\[
S_m^2 = \sum (t_j - \ln \delta_m(t_j) \cdot \tau_m)^2; \tag{9}
\]

\[
S_i^2 = \sum (t_j - \ln \delta_i(t_j) \cdot \tau_i)^2, \tag{10}
\]

Where \( t_j, \delta_m(t_j), \delta_i(t_j) \) are data of the experiment.

\[
\frac{\partial S_m^2}{\partial \tau_m} = \sum_{j=0}^{n} \left[ t_j + \ln \delta_m(t_j) \cdot \tau_m \right] \cdot \ln \delta_m(t_j) = 0; \tag{11}
\]

\[
\frac{\partial S_i^2}{\partial \tau_i} = \sum_{j=0}^{n} \left[ t_j + \ln \tilde{\delta}_i(t_j) \cdot \tau_i \right] \cdot \ln \tilde{\delta}_i(t_j) = 0 \tag{12}
\]

After simple transformations, we get:

\[
\tau_m = \frac{\sum_{j=0}^{n} (t_j \cdot \ln \delta_m(t_j))}{\sum_{j=0}^{n} (\ln \delta_m(t_j))^2}; \tag{13}
\]
\[
\tau_i = \frac{\sum_{j=0}^{n} (t_j \cdot \ln \delta_i (t_j))}{\sum_{j=0}^{n} (\ln \delta_i (t_j))^2}
\]

According to the results of the experiment:
\[\tau_m^* = 0.856 \text{ h}; \quad \tau_i^* = 0.323 \text{ h}.\]

Here, we check the conformity of the models to the original experimental statistics by estimating the coefficients of determination.

\[
n_{\delta_m}^* = \frac{1 - \frac{\sum_i (\delta_m (t_j) - \delta_m^* (t_j))^2}{\sum_i (\delta_m (t_j) - \delta_m^* (t_j))^2}}{1 + \frac{\sum_i (\delta_i (t_j) - \delta_i^* (t_j))^2}{\sum_i (\delta_i (t_j) - \delta_i^* (t_j))^2}}
\]

\[
n_{\delta_i}^* = \frac{1 - \frac{\sum_i (\delta_i (t_j) - \delta_i^* (t_j))^2}{\sum_i (\delta_i (t_j) - \delta_i^* (t_j))^2}}{1 + \frac{\sum_i (\delta_m (t_j) - \delta_m^* (t_j))^2}{\sum_i (\delta_m (t_j) - \delta_m^* (t_j))^2}}
\]

\[n_{\delta_m}^* = 0.905; \quad n_{\delta_i}^* = 0.764\]

According to the coefficients of determination, it can be concluded that the models correspond to the initial experimental data.

From figures (2) and (3), it follows that \(m(t)\) and \(i(t)\) are partially interrelated, and to a large extent, have differences according to the calculations (by 2 to 4 times). This is the evidence that the process of drying by electroosmosis is also influenced by another factor: it is likely that it concerns the effect of the Joule heat accumulated in the pulp. This process is specific and requires additional research, which will be conducted in a separate article.

As a result, it can be concluded that the parameters of models can vary. The latter will be implemented by the variation of the electric field at the electrodes of the installation, but this fact is a detailed implementation of the technological process [9].

The results of repeated experiments show that the mode of drying of electroosmosis and the mode of electrophoresis can be represented by exponents, but the exponents have different time constants.

It should be noted here that the processes of electroosmosis and electrophoresis can take place in an experimental dosage of pulp simultaneously: with a residual volume (mass) of water and technological dosage of a binder (liquid glass).

As the indirect measurements showed, the essence of the method is as follows: \(\Delta_1, \Delta_2, \ldots\) in this case, the pulp dries to a certain extent in a convective way [10]. This loss must be eliminated in the study of electroosmosis. This procedure will allow a more accurate assessment of the correlation between the electric current flowing through the pulp and the "loss" of its mass caused by electroosmosis.

After the conversion (deduction of mass loss, \(\Delta_1, \Delta_2 \ldots\)), the graph takes the form shown in figure 5:
Figure 4. The results of the experiments on the pulp drying by electroosmosis and electrophoresis, taking into account the mass loss of the pulp during reload.

Figure 5. The results of the experiments on the osprey drying by electroosmosis and electrophoresis, taking into account the mass loss of the pulp during a reboot after conversion.

\[
\begin{align*}
    m(t_1) &= \frac{m(t_1) + m(t')}{2} \\
    m(t_2) &= \frac{m(t_2) + m(t')}{2} \\
    \vdots
\end{align*}
\]

(17)

The parameter model is estimated according to (17). As its analytic transformation, we take the exponent:

\[ m_{oc}(t) = m_{oc}^{e^{-\frac{t}{\tau}}} \]  
\[ \delta_{noc}(t) = \frac{m_{oc}(t)}{m_{oc}(t_0)} = e^{-\frac{t}{\tau}} \]

where \( \tau \) — unknown parameter.

Similar calculations should be repeated to estimate the parameters of the electroosmosis current and electrophoresis (in the last cases, it is necessary to assess more accurately the changes in the mass of the pulp - increase or decrease).

Later, we get \( \delta_{noc}(t_i) \) and \( i_{oc}(t_i) \). With this in mind, we find estimates for the correlation functions.

\[
\begin{align*}
    r(\delta_{noc}, i_{oc}) &= \frac{k(\delta_{noc}, i_{oc})}{\delta(\delta_{noc})i(\delta_{noc})} = \\
    &\frac{\sum_1^n (\delta_{noc}(t_i) - m_{noc}(t_0))(i_{oc}(t_i) - I_{oc}(t_i))}{\sqrt{\frac{1}{n-1} \sum_1^n (\delta_{noc}(t_i) - m_{noc}(t_0))^2} \cdot \sqrt{\frac{1}{n-1} \sum_1^n (i_{oc}(t_i) - I_{oc}(t_i))^2}}
\end{align*}
\]

(18)

The data of indirect measurements and their analysis allows us to conclude that the process of electroosmosis and electrophoresis is manifested together. Their differentiation is difficult. Therefore, it will be necessary in the future to take advantage of the phenomenological estimates (the time constant and the time of censoring experimental data) based on experimental data [11]. In further experiments,
we will measure the mass of the pulp $m_j$ at different corresponding times $t_j$, where $j$ is the number of the time section: 
\[ j \in \{0,1,2,...n,...\} \]

3. Conclusions
In the course of this study, information was collected and analyzed in the perspective of producing an electroosmotic installation, in other words, a converter of colloidal polydisperse systems into capillary-porous by electroosmotic dehydration in order to reduce the residual moisture of sludge from sewage and the pulp and paper industry. The proposed model is an optimized installation. The analysis of the possible improvement of the performance of technological innovations in the field of environmental safety in industrial enterprises. Exponents were taken as models expressing the mass of the pulp as a function of drying time and the value of the electric current. According to the obtained coefficients of determination, the models were consistent with the initial experimental data. Exponential models were used to further optimize the process of converting colloidal polydisperse systems in capillary-porous. The studied model of the wet waste conversion into raw materials intended for being used as building materials according to the obtained experimental data can significantly reduce the costs of enterprises for recycling and increase the ecological level of the pulp and paper industry.

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