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Operating parameters of an energy-efficient electroosmotic device for dehydrating wastewater sludge from paper production

Parámetros de funcionamiento de un dispositivo electroosmótico energéticamente eficiente para deshidratar lodos de aguas residuales de la producción de papel

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ABSTRACT

The paper describes the design of an electroosmotic device for treating dehydration of water-mineral-organic wastewater sludge from paper production and a methodology for conducting experimental studies. As for regression equations for the reduction factor of the waste mass, specific indicators were presented: drainage fluid consumption, current strength, power consumption, and energy, depending on the voltage on the electrodes and the duration of treatment. Besides, the required waste treatment function depends on the voltage and the required waste concentration. Equations and graphs were presented. In terms of the intensity of fluid excretion, it was found that the most effective treatment is performed during the first 0.5–0.7 h. At a voltage of about 25 V, the processing time of waste (until the mass of waste is reduced to 1/3) is about 0.75 h, and at a voltage of less than 10 V, it is about 3–5 h. With a decrease in the voltage, the liquid withdrawal slows down faster. By the magnitude of the current, the separation process lasts for the first 0.7–1.0 h. By the nature of the change in the current, the process is homogeneous (differing only in intensity) at a voltage of more than 8 V. At a lower voltage, the intensity of waste separation by current strength and an increase in the duration of processing decreases sharply. The power consumption is actively growing in the first 1–2 h of processing, gradually slowing down. Then we found the proportionality of power to the applied voltage. The increase in power was associated with a decrease in the distance between the electrodes. With a decrease in the mass of waste less than 50% of the initial value, energy is less efficiently used for separating waste, and the observed increase in energy consumption during further processing sharply increases energy consumption. To reduce the final mass of waste and obtain their concentrate, it was necessary to increase energy consumption. Waste processing should be stopped when 1/3 of the initial waste mass remains due to the actual cessation of the separation of waste fractions with an active increase in energy consumption.

Keywords: Energy-efficient, Electroosmotic device, Water-mineral-organic waste, Electro-flotation plant for processing paper waste

RESUMEN

En el documento se describe el diseño de un dispositivo electroosmótico para tratar la deshidratación de lodos de aguas residuales de agua, minerales y orgánicos de la producción de papel y una metodología para realizar estudios experimentales. En cuanto a las ecuaciones de regresión para el factor de reducción de la masa residual, se presentaron indicadores específicos: consumo de fluido de drenaje, fuerza de corriente, consumo de energía y energía, dependiendo de la tensión en los electrodos y la duración del tratamiento. Además, la función de tratamiento de residuos requerida depende de la tensión y la concentración de residuos requerida. Se presentaron ecuaciones y gráficos. En términos de intensidad de excreción de fluido, se encontró que el tratamiento más efectivo se realiza durante las primeras 0,5–0,7 h. A una tensión de aproximadamente 25 V, el tiempo de procesamiento de los residuos hasta que la masa de residuos se reduce a 1/3 es de aproximadamente 0,75 h, y a una tensión de menos de 10 V, es de aproximadamente 3-5 h. Con una disminución en la tensión, la extracción de líquido se ralentiza más rápido. Por la magnitud de la corriente, el proceso de separación dura las primeras 0,7–1,0 h. Por la naturaleza del cambio en la corriente, el proceso es homogéneo (que difiere solo en intensidad) a una tensión de más de 8 V. A una tensión más baja, la intensidad de separación de residuos por fuerza de corriente y un aumento en la duración del procesamiento disminuye drásticamente. El consumo de energía está creciendo activamente en las primeras 1-2 h de procesamiento, disminuyendo gradualmente. Luego encontramos la proporcionalidad de la potencia al voltaje aplicado. El aumento de la potencia se asoció con una disminución de la distancia entre los electrodos. Con una disminución de la masa de residuos inferior al 50% del valor inicial, la energía se utiliza de manera menos eficiente para separar los residuos, y el aumento observado en el consumo de energía durante el procesamiento posterior aumenta considerablemente el consumo de energía. Para reducir la masa final de residuos y obtener su concentrado, era necesario aumentar el consumo de energía. El tratamiento de residuos debe detenerse cuando quede 1/3 de la masa de residuos inicial debido al cese real de la separación de fracciones de residuos con un aumento activo del consumo de energía.

Palabras clave: Eficiencia energética, Dispositivo electroosmótico, Residuos orgánicos minerales de agua, Planta de electro flotación para el procesamiento de residuos de papel.

1. INTRODUCTION

A special technical device (installation) is necessary to organize an experiment to study the possibility of using the effect of electro-osmosis for dehydration of water-mineral-organic waste.

In this case, the technical problem is the creation of an easy-to-operate electroosmotic device, applicable and economically beneficial for dehydration of water-mineral-organic waste.

The technical result of the study lies in the efficiency of dehydration by increasing the contact area (Ryzhakov, Kholudeneva & Ryzhakov, 2014; Tarasov, Konovalov, Zaitsev & Rodionov, 2018; Zaitsev, Konovalov, Gumarov & Rodionov, 2018). The research problem has been solved. An electroosmotic device for dehydrating a porous material contains an electrically insulating housing with electrodes (which are an anode made in the form of a conductive cover moving vertically inside the housing and a cathode made in the form of a conductive perforated bottom of the housing, forming a space for the dehydrated material between them). Thus, the surface of the electrodes interacting with the dehydrated porous material is provided with pointed protrusions (Chernyakhovskaya, 2008; Ryzhakov & Kholudeneva, 2013). The results of studies of the characteristics of the insulation market and their use in the organization of production of Ecoplit are given (Ryzhakov, Kholudeneva & Ryzhakov, 2015; Ryzhakov, Kupryashin & Kholudeneva, 2013).

Peaked projections can be formed on the anode or cathode, while peaked protrusions can be made in the form of pyramids. The conductive cover preferably contains stiffening ribs and a unit connecting it to a device for moving the conductive cover inside the electrically insulating body. The electro-osmosis device is preferably configured to be installed under the perforated bottom of the pallet and adjust the inclination angle. The insulating body is preferably perforated.

Fig. 1 shows the general view of the electroosmotic device, partially in section; Fig. 2 presents its projection on the axial plane.

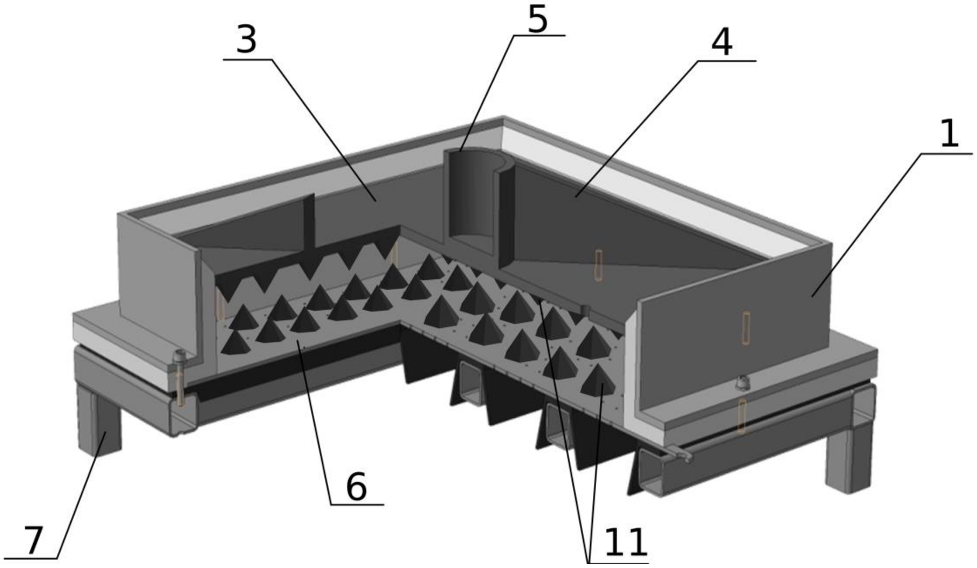


Figure 1: General view of an electroosmotic device

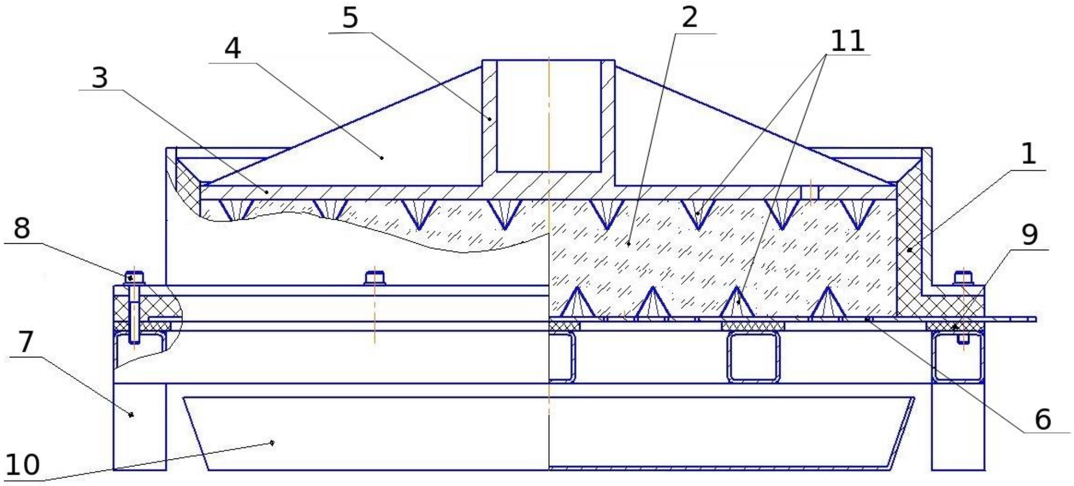


Figure 2: Projection of the electroosmotic device on the axial plane

The electroosmotic device is an electrically insulating body (1) with electrodes, which form a space between themselves for the material to be dehydrated (2).

The anode is made in the form of a conductive cover (3), which vertically moves inside the housing (1) under its weight, under the action of a press or a clamping screw. To ensure the necessary strength and functionality, we equipped the cover (3) with stiffening ribs (4) and a connection unit (5) with a device that provides movement (press or clamping screw).

The cathode is made in the form of a conductive perforated bottom (6), mounted on the frame (7) with bolts (8) and insulating spacers (9). The frame holds body (1) above pallet (10) with the possibility of adjusting the angle of inclination (to simplify the drainage of the released moisture).

The surface of the anode and cathode, interacting with the dehydrated porous material (2), is provided with pointed projections (11) in the form of cones made of the same material as the electrodes.

2. MATERIALS AND METHODS

To organize the experiment, we varied the input voltage on the installation plates in the following order: U = 4, 8, 12, 16, 20, 24, 28 V.

For each of the voltage values, we determined the optimal exposure time empirically. It was advisable to dehydrate to the value of the current strength on the plates of the installation i (t) = [0 ÷ 0.15] A. Thus, based on the results of the experiments, the time intervals for dehydration were established, as well as the values of the electric current and mass (in fractional values from the initial) at a time with a given step tint = 0.25 h. The experimental data were given as the average value over 47 repetitions.

Table 1: Time intervals for dehydration of water-mineral-organic waste from pulp and paper production, the values of the electric current and mass (in fractional values from the initial) at a time with a given step tint = 0.25 h

	t	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5	4.75	5
U=4	I	0.9	0.76	0.71	0.69	0.65	0.61	0.58	0.55	0.51	0.49	0.46	0.42	0.39	0.35	0.31	0.28	0.26	0.21	0.18	0.15	0.11
	M	1	0.91	0.86	0.82	0.78	0.75	0.71	0.68	0.65	0.61	0.58	0.56	0.53	0.5	0.47	0.44	0.41	0.39	0.36	0.35	0.34
U=8	I	1.75	1.49	1.23	1.09	0.87	0.82	0.75	0.65	0.58	0.51	0.47	0.43	0.35	0.2	0.1						
	M	1	0.85	0.73	0.65	0.57	0.49	0.46	0.4	0.37	0.36	0.35	0.35	0.34	0.34	0.33						
U=12	I	2.9	1.52	1.24	1.11	1.03	0.89	0.71	0.56	0.39	0.21	0.12										
	M	1	0.74	0.69	0.63	0.58	0.54	0.5	0.46	0.42	0.38	0.33										
U=16	I	3.95	1.91	1.51	1.28	0.91	0.64	0.26	0.11													
	M	1	0.69	0.57	0.49	0.46	0.42	0.39	0.34													
U=20	I	4.7	2.31	1.84	1.31	0.61	0.14															

	M	1	0.65	0.52	0.41	0.38	0.33															
U=24	I	5.5	2.86	1.12	0.54	0.14																
	M	1	0.6	0.42	0.35	0.33																
U=28	I	6.3	3.1	1.4	0.2																	
	M	1	0.54	0.42	0.32																	

For different voltage values, the values of the resistivity of water-mineral-organic waste were determined: **ρ** [Ohm · m] at the beginning, in the middle, and at the end of the electroosmotic dehydration process. The results are shown in Table 2, where l [m] is the distance between the installation plates.

Table 2: Experimental values of the specific resistance of mineral water - organic waste at the beginning, in the middle, and at the end of the electroosmotic dehydration process

U	**ρ [Ohm • m]**		
	Beginning	**Middle**	**End**
	l=0.38	*l=0.17*	*l=0.12*
4	1.871345	8.184143	533.3333
8	1.924812	11.58371	533.3333
12	1.742287	12.69002	581.8182
16	1.70553	15.21093	568.8889
20	1.791713	11.69163	571.4286
24	1.837321	10.65483	533.3333
28	1.871345	8.500949	497.7778
Average value ρ	1.820622	11.2166	545.7019

After regression processing, the results were presented in the form of statistical models. When studying the parameters of an electroosmotic plant for liquid waste of paper production, we removed water from the composition of a portion of liquid waste equal to 70 kg. As a result, the moisture content of the waste decreased.

3. RESULTS AND DISCUSSION

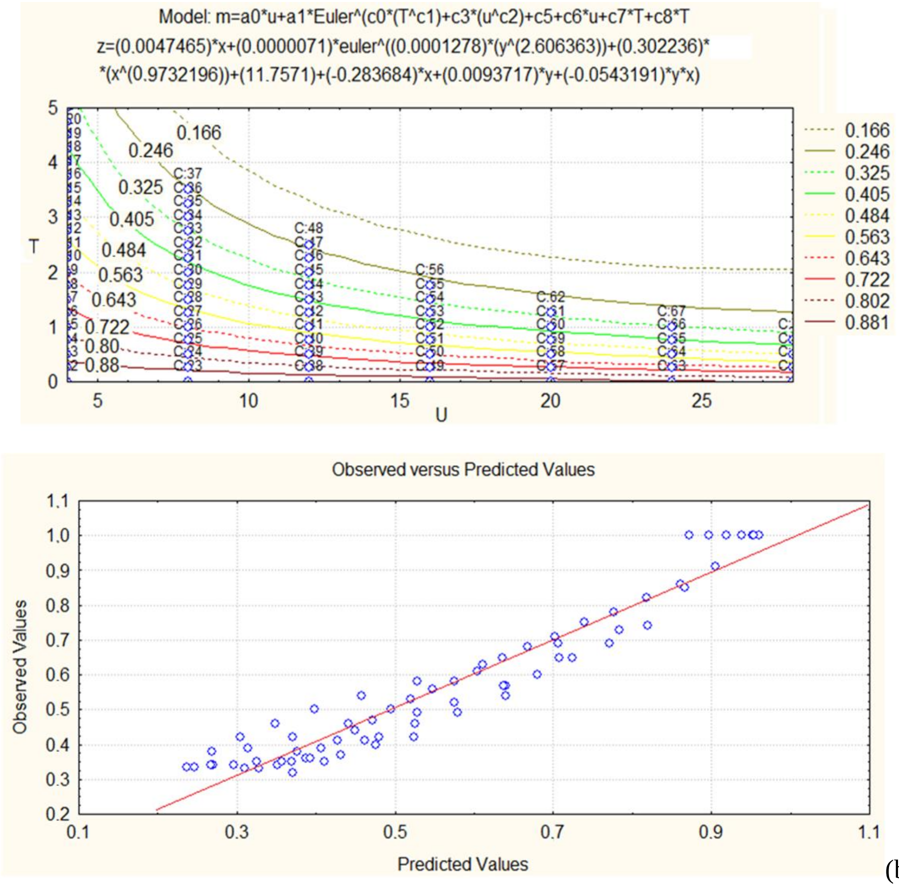
As a result of statistical processing of the obtained experimental results, regression expressions were established.

During the operation of the electro-flotation settler, the movement of pollutant particles with a lower density than water was carried up to the anode. Then water accumulated at the conductive perforated bottom of the cathode. As a result of drainage through the perforated bottom, the water was discharged. Thus, the mass of waste in the internal space of the installation was reduced in proportion to the reduction factor of the amount of waste. The waste reduction coefficient m (kg/kg - the ratio of the final amount of waste to the initial one) depends on the duration of the electro-flotation effect T (h) and the voltage U (V) applied to the electrodes. The waste reduction factor is described by the following expression:

$$m = 0.00475 \cdot U + 7.1 \cdot 10^{-6} \cdot e^{\left(11.757 + 1.28 \cdot 10^{-4} \cdot T^{2.6} + 0.3 \cdot U^{0.97} - 0.28 \cdot U + 0.0094 \cdot T - 0.054 \cdot T \cdot U\right)} \quad (1)$$

A statistical model with the F-test = 0.980261 and Pearson's correlation coefficient R = 0.959878 was adequate. The correspondence of the numerical values of the calculated values according to the statistical model to the experimental results is shown in (Fig. 2.b). According to the F-test, the location of these values next to the red line indicates good convergence of the results, which is confirmed by a confidence probability of about 98%.

The change in the waste reduction coefficient was hyperbolic in terms of the influence of stress and processing time. Increasing the voltage reduces the processing time to a constant value of the studied coefficient. With the coefficient values of reducing the amount of waste according to the model m≤0.25 (less than 0.33), no significant improvement in the quality of waste was observed. Also, increasing the processing time did not significantly improve this factor.



(a)

(b)

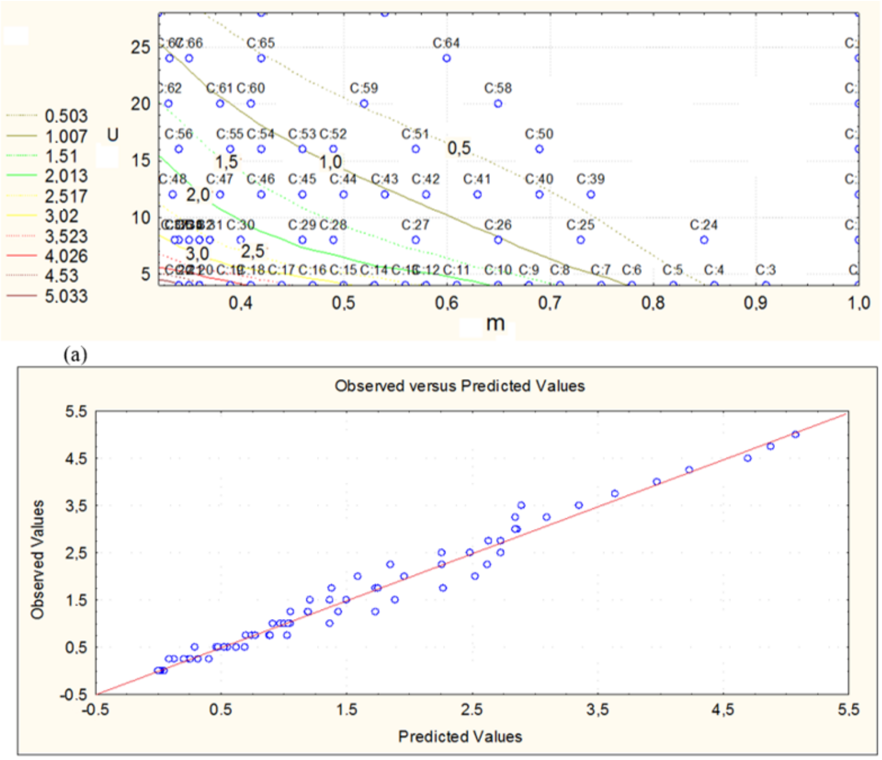
Figure 2: Graph of the change in the waste reduction coefficient m (kg/kg of waste) depending on the duration of electro-flotation treatment T (h) and the voltage between the electrodes U (V): (a) – two-dimensional lines of equal output of the statistical model; (b) – a graph of the correspondence of the calculated values of the statistical model to the experimental values

The required duration T (h) of waste treatment, depending on the degree of dehydration and applied voltage (Fig. 3), was as follows:

$$T = 1.77 \cdot e^{\left(-1.37 - 0.00083 \cdot m^{1.72} \cdot U^{2.73} + 3.336 \cdot U^{-5.69} - 3.75 \cdot m^{5.81} + 4.37/U + 0.456/m\right)}, \tag{2}$$

A statistical model with the F-test = 0.910952 and Pearson’s correlation coefficient R = 0.987175 was adequate.

The waste reduction coefficient significantly affects the required duration of waste processing. At a voltage of about 25V, the processing time of waste up to m = 0.3 is about 0.75 hours, and less than 10V - about 3-5 hours. With a decrease in voltage, the nature of the deceleration of fluid withdrawal accelerates.



(a)

(b)

(b)

Figure 3: Graph of changes in the duration of processing T (h) depending on the coefficient of reduction of the amount of waste m (kg/kg of waste) and the voltage between the electrodes U (V): (a) – two-dimensional lines of equal output of the statistical model; (b) – a graph of the correspondence of the calculated values of the statistical model to the experimental values

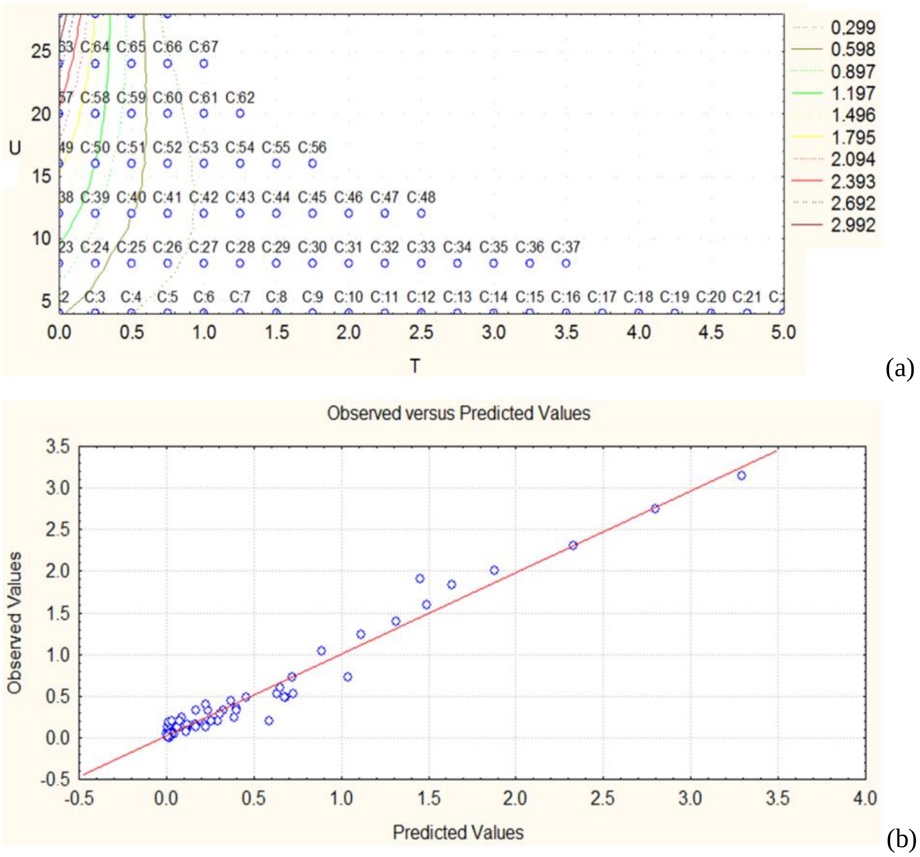
Instantaneous values of the specific hourly water consumption (Fig. 4) through the perforated bottom Q ((kg/h)/kg waste) were as follows:

$$Q = 0.0493 \cdot e^{\left(-0.00243 \cdot T^{1.7} \cdot U^{2.1} + 1.79 \cdot U^{0.255} - 1.29 \cdot T^{0.76}\right)}, \qquad (3)$$

A statistical model with the F-test = 0.961136 and Pearson’s correlation coefficient R = 0.982532 was adequate.

The liquid flow rate through the perforated bottom was most intense in the first 0.5–0.75 hours, regardless of the voltage. At a voltage of 12 V or more, the flow of liquid through the bottom in the first 0.5 hours was the most intense. Later, consumption stabilized and had values less than 0.3 (kg/h) per 1 kg of waste.

At low voltage, the liquid flow rate at the outflow of liquid was low throughout the waste processing. Therefore, in terms of the intensity of fluid withdrawal, the most effective treatment was within 0.5–0.7 hours.



(a)

(b)

Figure 4: The graph of the change in the flow rate Q ((kg/s)/kg of waste) of the removed waste depending on the duration of treatment T (h) and the voltage between the electrodes U (V): (a) – two-dimensional lines of equal output of the statistical model; (b) – a graph of the correspondence of the calculated values of the statistical model to the experimental values

The change in the specific current I (A / m2 of the cathode bottom) passing through the electrodes can be described by the following expression:

$$I = -0.0455\cdot U + 0.053\cdot e^{\left(-12.5+36.84\cdot T^{1.002}+15.75\cdot U^{0.065}-0.014\cdot U-36.77\cdot T-0.1\cdot T\cdot U\right)}, \qquad (4)$$

A statistical model with the F-test = 0.975195 and Pearson’s correlation coefficient R = 0.989532 was adequate.

An increase in voltage promoted an increase in the value of the current. Over time, the current decreased. At a voltage of more than 8 V, the current during the first hour of processing decreased to 6 A/m2 of the bottom and then stabilized. At a lower voltage, the indicated current was observed only up to 5 V. The current up to 2.5 A/m2 of the bottom dropped in 1.0–3.2 h, depending on the applied voltage (at higher voltage, faster). The dependence was close to linear. The line of equal yield I = 2.397 (Fig. 5.a) in its outlines was close to the similar line m = 0.484 (see Fig. 2.a); the distance between the electrodes was the same. Regardless of voltage, with a 50% reduction in waste mass, the current strength was reduced to 2.4 A/m2 at the bottom. Analyzing the nature of the change in current strength, we can assert that the process was homogeneous (differed only in intensity) at a voltage of more than 8 V. In terms of the magnitude of the current, the separation process lasted for the first 0.75–1.0 hours. At a lower voltage, no intense stress effect on the waste separation process was observed.

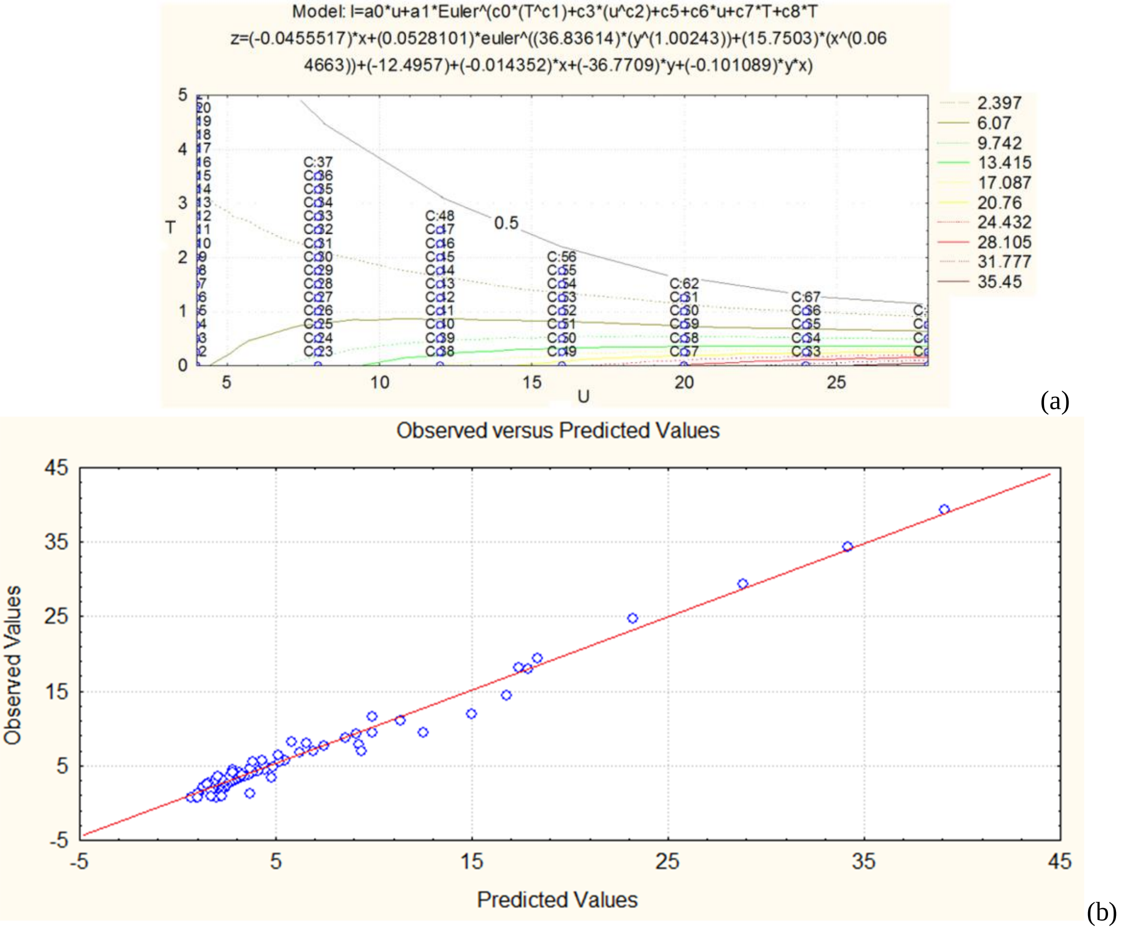


Figure 5: The graph of the change in the magnitude of the current I (A/m2 of the bottom) depending on the duration of processing T (h) and the voltage between the electrodes U (V): (a) – two-dimensional lines of equal output of the statistical model; (b) – a graph of the correspondence of the calculated values of the statistical model to the experimental values.

Specific power consumption of the electric flotation unit P (W/kg of waste) can be described by the following expression:

$$P = 0.0345 \cdot U - 0.00037 \cdot e^{\left(-9.1 - 0.268 \cdot T^{0.716} \cdot U^{0.64} + 14.3 \cdot U^{0.052} - 0.98/U\right)}, \tag{5}$$

A statistical model with the F-test = 0.972592 and Pearson’s correlation coefficient R = 0.993094 was adequate.

Analysis of changes in power consumption shows its active growth in the first 1–2 h, gradually slowing down. Later, stabilization and proportionality to the supplied voltage were observed. The increase in power was associated with a decrease in the distance between the electrodes, which reduces the resistance of the waste. Taking into account the nature of the change in the current strength with a decrease in the mass of waste by more than 50% (m≤0.5), the increase in power was not connected with an improvement in the separation of waste fractions.

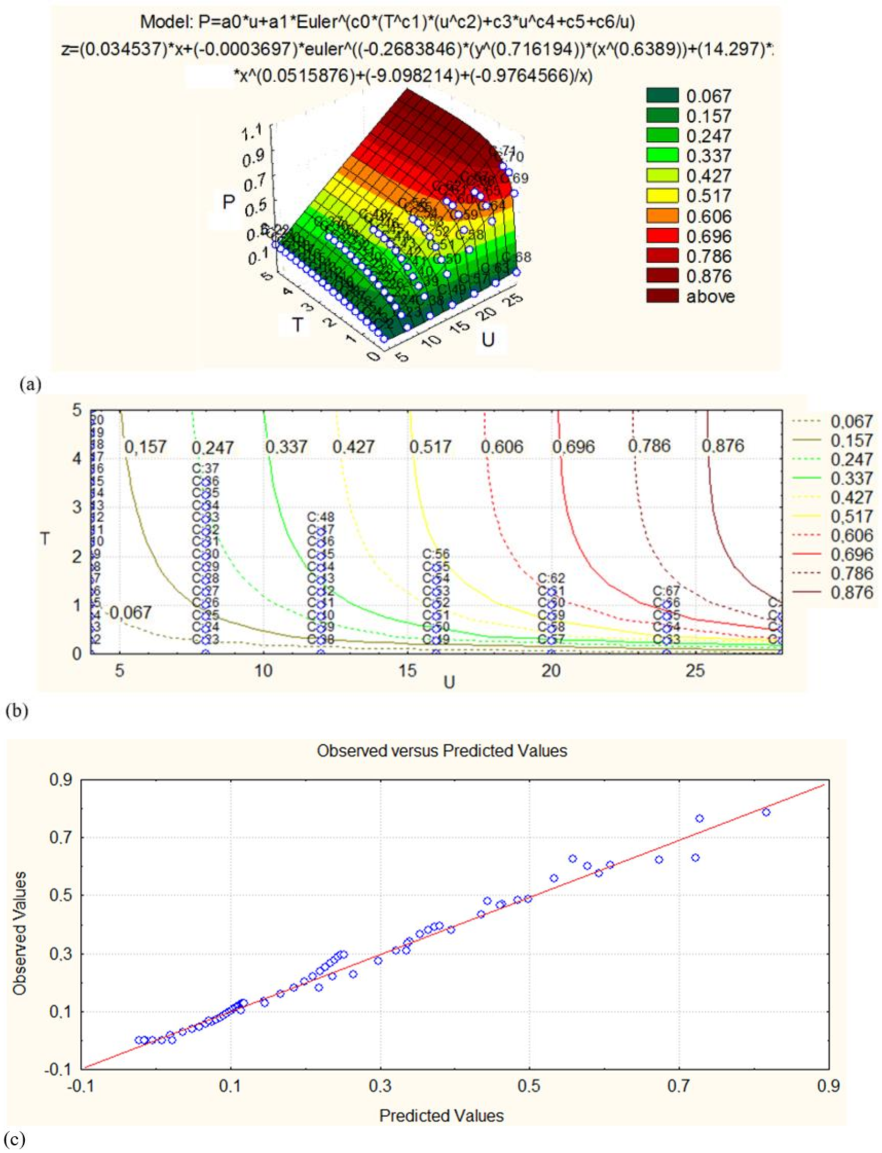


Figure 6: Graph of changes in power consumption P (kW/kg of waste) depending on the duration of treatment T (h) and the voltage between the electrodes U (V): (a) – response surface of the statistical model; (b) – two-dimensional lines of equal output of the statistical model; (c) – a graph of the correspondence of the calculated values of the statistical model to the experimental values

Specific energy consumption (work) of the electro-flotation plant A (J/kg of initial waste) can be described by the following expression:

$$A = -7.4\cdot 10^{-8}\cdot U + 8.1\cdot 10^{-6}\cdot e^{\left(-1.95+2.43\cdot T^{0.072}\cdot U^{0.242}+0.358\cdot U^{-0.924}-2.58/U\right)}, \qquad (6)$$

A statistical model with the F-test = 0.871255 and Pearson's correlation coefficient R = 0.98869 was adequate. The F-test confidence level of the model was about 87%. It was not possible to raise it to 90%.
Analysis of the graph (Fig. 7.a) indicates the relationship between energy consumption and power consumption function. At the same time, the accumulative nature of the consumed power affected the constant increase in the consumed energy. If, with a decrease in the mass of waste less than 50% of the initial value (m≤0.5), energy is less efficiently used for separating waste, then energy consumption during further processing will dramatically increase energy consumption. However, to reduce the mass of waste and obtain their concentrate, it was necessary to increase energy consumption. According to the model, at m≤0.246 (see Fig. 2.a), and according to the actual data at m≤0.32, the separation practically stopped (the values of *m* did not change significantly), then the processing should also stop at the remainder of 1/3 of the initial mass of the waste.

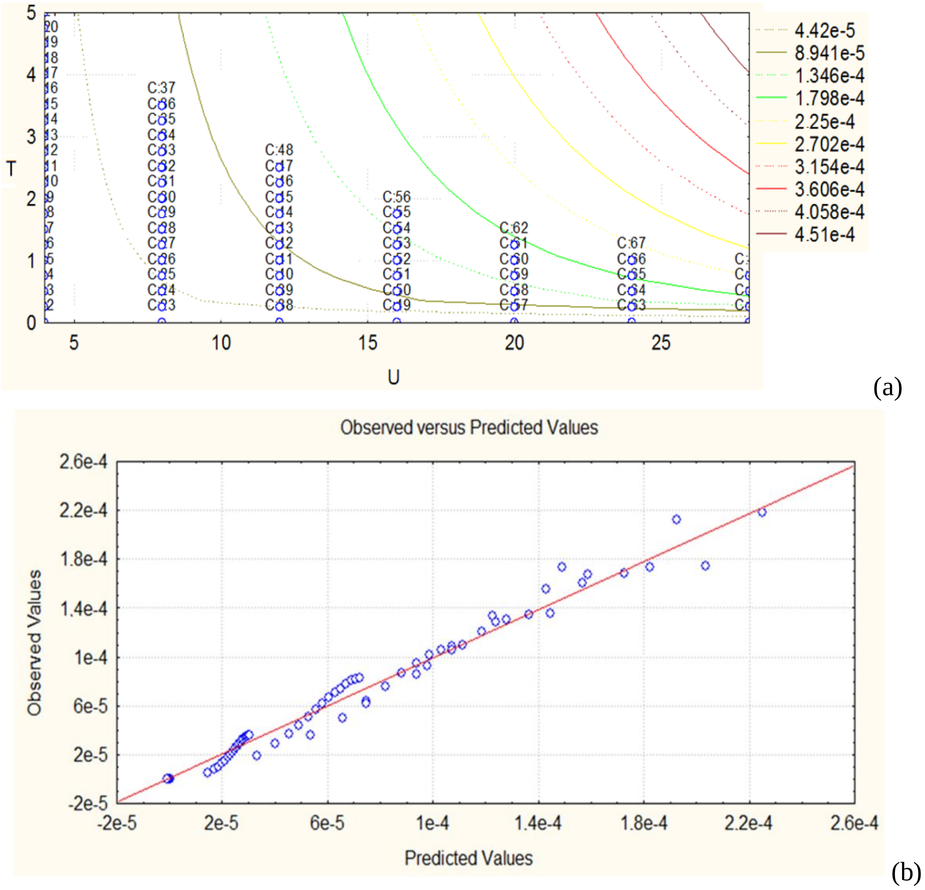


Figure 7: The graph of the change in the expended energy-work A (J/kg of waste) depending on the processing time T (h) and the voltage between the electrodes U (V): (a) – two-dimensional lines of equal output of the statistical model; (b) – a graph of the correspondence of the calculated values of the statistical model to the experimental values

When designing equipment for electro-flotation waste treatment, we preset the value of the voltage supplied to the electrodes, and according to formulae 2 and 3, we determined the duration of waste processing. Taking into account additional operations, such as pouring waste into the installation, removing contaminants, and other preparatory and final measures, we identified the duration of the cycle (Kholudeneva & Efremova, 2019; Presidential Executive Office, 2011; Russian Federation, 2008). Given the approximate cycle time T_C = 1.5–2.0 hours, the utilization rate of working time, the height of the treated waste layer about = h =0.5 m, and the possible number of waste processing cycles per day (pcs.), we can determine the total required area of the cathode bottom (m^2).

$$S = \frac{24 \cdot V \cdot \tau}{h \cdot N \cdot T_C}. \tag{8}$$

Taking into account Formula 4 and Fig. 5, the maximum value of the specific current strength was determined, and given the total area of the cathode bottom, the total current strength directed to the waste processing area was revealed.

Based on the daily volume of production waste V (m^3) and its initial density of the order of ρ =1,050 kg / m3, the daily mass of waste M (kg) was determined as follows:

$$M = V \cdot \rho. \tag{7}$$

Taking into account Formula 5 and Fig. 6, the maximum value of the specific power consumption was determined, and given the daily mass of waste, the required power for the operation of the waste processing section was identified. Considering Formula 6 and Fig. 7, the specific energy consumption was established, and taking into account the daily mass of waste, the daily energy consumption for waste processing was defined. The minimum diameter of the drainage water drainage pipeline was revealed, taking into account Formula 3 and Fig. 4 and the initial mass of waste in the installation. It should be borne in mind that the obtained values were related directly to the electro-flotation plant. Thus, the results obtained make it possible to design a waste treatment area at an electro-flotation unit according to the main indicators.

4. CONCLUSION

The results of experimental data provide the necessary information for the design of an electro-flotation plant for processing paper waste. The obtained regression equations based on statistical data processing were adequate and made it possible to model a number of the main indicators of the process under study.
In terms of the intensity of fluid withdrawal, the most effective treatment was within 0.5–0.7 hours. At a voltage of about 25 V, the processing time of the waste (until the mass of waste was reduced to 1/3) was about 0.75 h, and at a voltage of less than 10 V, it was about 3–5 h. With a decrease in voltage, the nature of the deceleration of fluid withdrawal accelerated.

In terms of current strength, the separation process lasted for the first 0.7–1.0 hours. By the nature of the change in the current strength, the process was homogeneous (differing only in intensity) at a voltage of more than 8 V. At a lower voltage, the intensity of waste separation by current strength and an increase in the duration of treatment sharply decreased.

The power consumption was actively growing in the first 1–2 h of processing, gradually slowing down. Later, there was the proportionality of the power to the applied voltage. The increase in power was associated with a decrease in the distance between the electrodes.

With a decrease in the mass of waste to less than 50% of the initial value, energy was less efficiently used for separating waste, and an increase in energy consumption during further processing sharply increased energy consumption. To reduce the final mass of the waste and obtain its concentrate, it was necessary to increase energy consumption. Waste treatment should stop when 1/3 of the initial waste mass remains due to the actual termination (process insignificance) of the separation of waste fractions with an active increase in energy consumption.

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