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Results of experimental studies of sunflower oil purification by means of electric field in an electrostatic precipitator

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Abstract: Sunflower oil is an indispensable product of functional purpose, which at its reasonable consumption increases immunity, cleanses the body of toxins, improves the brain and heart, and as a result, having a complex effect on the whole body provides an undeniable benefit to human health. Modern development of sunflower oil purification technologies involves improvement of existing and development of new methods and technical means, environmentally safe, accompanied by minimum energy consumption and characterised by increased indicators of technological efficiency, providing the possibility of separation of unnecessary impurities and preservation of valuable components extracted from the oil for their further use. Such a promising method is the purification of sunflower oil in the electric field. The paper considers the possibility of cleaning sunflower oil by an electrostatic precipitator from suspended particles by means of an electric field acting on them. The planned experiment is described and the process of removal of unnecessary impurities is analysed. The justification of the factors and parameters of the experimental study is considered separately. The dependences of the electrical characteristics of oil on the parameters of the purification process are established. Analytical expressions for empirical dependences of energy parameters of the purification process, mode and parameters of ESP operation are determined. The adequacy of theoretical and experimental results has been checked. Having analysed the obtained results, the optimum parameters of effective cleaning and ESP operation were determined, which on the basis of the obtained regression equations should be the following: voltage at ESP electrodes U = 4.4 kV, interelectrode distance b = 0.01 m, oil temperature at the inletθ = 42°C. The calculated energy consumption at these parameters is equal to 12 W-h/kg.

Keywords: electrostatic precipitator, sunflower oil purification, electrophoresis, electric field, sunflower oil

1. Introduction

Sunflower oil occupies one of the leading places in the diet. It contains five times more polyunsaturated fatty acids than olive oil, which is extremely important for the heart and cardiovascular system as a whole, prevents the onset of such a disease as atherosclerosis, improves blood circulation, regulates cholesterol levels. In this regard, it is subject to certain requirements that contribute to the preservation of human health [1, 2].

Sunflower oil production includes the following operations: incoming seeds are cleaned of debris, dried, husks are separated from the seeds, the grains themselves are crushed to form mint, oil from which is produced by two methods: pressing and extraction.

The hot-pressing technology involves preheating the mint to 100°C with the addition of moisture to avoid burning, and then pressing out the oil on presses. The cold-pressing method excludes preheating of raw materials, so the product manages to preserve the maximum amount of vitamins. Sunflower oil extraction involves the use of special solvents that are safe for health and the environment. The process is carried out in special containers, in which the seed meal - the residue after processing and miscella - oil solution are obtained from the seeds. The oil is "extracted" from the meal and miscella, which undergoes sedimentation, filtration and further processing.

Sunflower oil is also refined, which involves some cycle of sequential operations: 1) removal of foreign impurities - the product is sedimented, filtered and centrifuged; 2) treatment with a certain amount of hot water; 3) removal of excessive amounts of fatty compounds; 4) removal of pigments and volatile compounds from the oil; 5) freezing process with removal of waxes. Refined oil is ideal for heat treatment, while unrefined oil is treated minimally, usually by filtering to remove heavy impurities. Unrefined oil retains all the beneficial properties of the product and can be consumed raw [3].

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Deviation from GOST requirements for sunflower oil production and storage can lead to irreparable consequences - oil accumulates harmful components, so special attention should be paid to the performance of these operations accordance with the regulations. It should be remembered that when obtaining oil from seeds by pressing, in addition to the main group of trialglycerols, structural lipids, which determine the colour, taste and smell characteristic of sunflower oil, as well as solid particles of pulp, water, waxes, paraffins, polycyclic aromatic hydrocarbons, purification of herbicides and pesticides, products of microflora [4,5,6].

Today, more and more attention is being paid to the use of environmentally friendly and food-safe technologies, paying special attention to the use of electrophysical methods and techniques that allow both the cultivation of raw materials for the oil and fat industry [7,8,9] and the purification of edible oils, purification and refining [10,11,12].

The paper presents an analysis and discussion of a study on sunflower oil purification using electric field in an electrostatic precipitator.

2. Objects and methods

The process whose ultimate goal is the separation of trialglycerols, free and other lipid groups and impurities from the resulting oil is called oil purification or refining. In small-scale agricultural enterprises, the sunflower oil obtained after pressing is subjected to a refining process that can be depicted as follows (Figure 1).

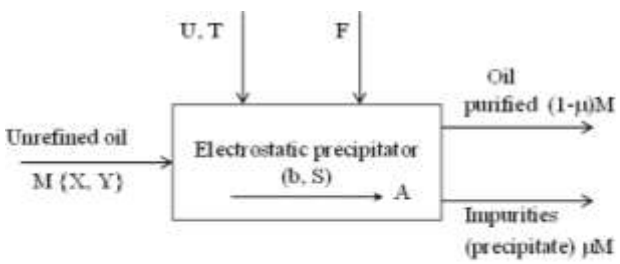

Fig. 1. Sunflower oil purification system in an electrostatic filter: X - uncontrolled oil parameters; Y - controlled oil parameters; U - voltage on the electrodes; T- is the time the oil is in the electric field; b, S - geometric dimensions of the electrostatic filter; M - mass of crude oil; μ - mass fraction of impurities in oil; F - disturbing random factors

The crude sunflower oil coming out of the press is characterised by some contamination with mechanical impurities and components of the oil itself, which in the process of cleaning should be removed or their concentration should be reduced to the minimum allowed by the quality standard. Oil purification is supposed to be carried out in an electrostatic precipitator. The parameters of the purification process are voltage and purification time, and the parameters of the electrostatic precipitator are its geometrical dimensions, including the interelectrode distance and the number of electrodes. The following parameters of energy consumption should be considered as determining parameters: 1) voltage applied to the electrodes; 2) electrophoresis time to complete oil purification; 3) interelectrode distance.

At the same time, it is impossible to assume a priori the value of any of the introduced parameters. This is due to their mutual influence, which has not yet been definitely established [10,11].

Thus, with an increase in voltage, a decrease in the time of the purification process can occur. However, taking into account that in the electrophoresis process some time is spent on creation of dipoles and aggregation of particles into larger structures, a proportional decrease in the duration of the purification process can hardly be expected.

Increasing the inter-electrode distance, on the one hand, will increase the mass of oil to be cleaned, but on the other hand, it will increase the time of movement of aggregated particles, that is, it may increase the cleaning time. Reducing the inter-electrode distance, on the other hand, will require a reduction in voltage to prevent electrical breakdown.

Thus, the task of searching for the most acceptable cleaning and electrostatic precipitator parameters from the point of view of the set goal is confirmed.

The purpose of the experimental study of sunflower oil purification process is:

- obtaining static data for realisation of theoretical provisions;
- verification of theoretical results;
- refinement of optimal parameters of the purification process.

The following **tasks** were carried out during the experimental research:

- justification of factors and parameters of experimental studies;
- determination of the number of experiments and their repetitions, and justification of the reliability of the obtained experimental data;
- establishing dependences of the electrical characteristics of oil on the parameters and duration of the cleaning process: $R = f(U, b,, T)$; $\varepsilon = f(U, b,, T)$;
- establishment of empirical dependences of energy parameters of the process on ESP parameters;
- adequacy of theoretical and experimental results.

The methods of probability theory and mathematical statistics are used to process experimental data. Practically mass calculations were carried out using the standard Microsoft Excel software package.

The criteria of the cleaning process and ESP are determined by the following parameters: R - resistance to direct current; ε - dielectric constant of oil; η - viscosity of oil. These parameters in turn depend on the physical characteristics of the oil - its temperature and moisture content.

Since ultimately in the electrophoresis process the aggregated impurity particles are deposited on the electrode and then run off from it, the optimal range of variation of physical characteristics will be the mode of deposition. The mode of deposition of impurities from sunflower oil in the electric field is determined by patterns characteristic of natural settling. As a rule, the products determined in the purification process are deposited on the positive electrode at a temperature of 30-60°C.

When dehydrating sunflower oil, it must be taken into account that the solubility of water increases with increasing temperature. This requires increased energy consumption for moisture removal. When selecting the temperature mode of electrodeposition, the product properties, the desired degree of purification and the conditions of the electrophoresis process should be taken into account. The oil in the tanks installed in oil shops has a temperature of 18-22°C, and leaving the press has a temperature of 80-100°C [3,4]. It is this range that it is reasonable to adopt when planning the experiment.

As follows from the theory of the electrophoresis process, one of the most important factors in the purification of sunflower oil using an electric field is its strength [12,13]. The field strength between the electrodes is determined by the voltage applied to them, the distance and their shape. In the simplest case, for plane-parallel electrodes, the field strength is constant in the entire volume between the electrodes.

For rod electrodes, the maximum field strength is observed on the surface of the rods, while the minimum field strength is observed in the plane equidistant from the electrodes opposite in sign. For chamber electrodes, the maximum field strength will be on the outer surface of the inner electrode, the minimum - on the inner surface of the outer electrode [14].

The increase in ESP performance with decreasing electrode spacing is attributed to the following factors:

- The time required for the movement of the separated particles to the electrodes is reduced;
- sizes of separated particles remain the same, the conditions of particle aggregation under the influence of polarisation are improved;
- the hydraulic regime of the purified product movement is improved as a result of reducing its circulation in the apparatus.

Based on the above and preliminary studies, the limits of variation of the factors were determined.

So it was experimentally established that at voltage less than 3 kV, oil purification practically does not occur, and at voltage higher than 10 kV there is intensive oil movement, which leads to "washing" of fuse from the electrodes. Based on the conditions of electrical breakdown and ESP design, the distance between the electrodes should be at least 0.005 m

In order to realise the theory of electrophoresis and analytical determination of the parameters of the purification process and the electrostatic precipitator, it is necessary to have data on the electrical parameters of sunflower oil (dielectric permittivity, DC and AC resistance) [13,15,16,17].

In this connection it is necessary to carry out preliminary experiments, as a result of which the following dependences are obtained: $R = f(\theta, U)$; $z = f(\theta, U)$; $\varepsilon = f(\theta, U)$; $\eta = f(\theta)$ - where R - resistance of oil to direct current, Ohm; z - resistance of oil to alternating current, Ohm; θ - temperature of oil,° C; U - voltage between electrodes, V; ε - dielectric constant; η - viscosity of oil.

The resistance of oil to direct (alternating) current was determined by Ohm's law, with voltage applied to the electrodes of the ESP. Since the resistance of oil to alternating current is active-capacitive, the capacitive resistance was calculated by the formula:

$$X_C = \sqrt{z^2 - R^2} . \quad (1)$$

Having determined the capacitance, the capacitance and then the dielectric constant were calculated using the formulas:

$$C = \frac{1}{2 \cdot \pi \cdot f \cdot X_c} , \quad (2)$$

where f is the frequency of the supply voltage, $f=50$ *Hz.*

$$\varepsilon = \frac{C \cdot b}{\varepsilon_0 \cdot S} . \quad (3)$$

where ε_0 is the electrical constant.

The electrical parameters of the oil were determined for the above temperature range and electric field strength. In addition, oil with moisture content of 0.15% and 1.2% was studied. Seven repetitions of experiments were carried out in the experiment.

To determine the reliability of the obtained experimental data, a series of experiments were checked for homogeneity. That is, the condition that deviations of oil resistance values to direct and alternating current and dielectric permittivity from the mean value are random and not significant was checked. For this purpose, the corrected dispersions in each series of experiments with the same parameters were calculated and the Cochran criterion was calculated using the formulas:

$$D_j = \frac{\Sigma_j \left(x_{ji} - \bar{x}_j\right)^2}{n-1} , \quad (4)$$

$$G = \frac{D_{MAX}}{\Sigma_j D_j} , \quad (5)$$

where D_j is the corrected variance in the j-th series of experiments; x_{ji} is the value of the studied variable in the i-th experiment of *the j-th* series; $\overline{x_j}$ is the mathematical expectation of the variable in the *j-th* series of experiments; D_{MAX} is the maximum value of the corrected variance in n experiments; n is the number of experiments.

For the convenience of using experimentally obtained characteristics of sunflower oil, they are described by polynomials of the form:

$$Y = a_n \cdot x^n + a_{n-1} \cdot x^{n-1} + \ldots + a_0 . \quad (6)$$

where Y - sunflower oil parameter; a_j - polynomial coefficients; x_j - experiment factor.

The "Trend Line" function of the standard Microsoft Excel package is used to calculate the coefficients of the polynomial.

The coefficients of the linear regression equation were calculated to account for the complex impact of factors:

$$R = a_0 + a_1 \cdot U + a_2 \cdot \theta + a_3 \cdot \eta + a_4 \cdot \theta^2 + a_5 \cdot \eta^2 + a_6 \cdot \theta \cdot \eta \cdot \quad (7)$$

To calculate the regression coefficients we used the "Linear Regression" function of the standard Microsoft Excel software package. Figure 2 shows in what form the required function is depicted on the Microsoft Excel sheet.

	A	B	C	D	E	F
1	a_n	a_{n-1}	...	a_2	a_1	a_0
2	se_n	se_{n-1}	...	se_2	se_1	se_0
3	R^2		...			
4	F		...			
5	se_{reg}	se_{resid}	...			

Fig. 2. View of the "Linear Regression" display on a Microsoft Excel sheet

In this case, the dependence between the desired parameter and the experimental factors is determined by the determinacy coefficient R^2 (cell A3).

3. Results and discussion

To assess the significance of the found dependence (to check whether this dependence is regular or random), the Fisher-Snedecor criterion is applied, the observed value of which is placed in cell A4 (Figure 2). The observed value should not be less than the tabulated value, chosen according to the significance level, which isα = 0.5, and degrees of freedom $v_1 = 5$ and $v_2 = 3$. The degrees of freedom are defined as follows: $v_1 = k, v_2 = m - (k-1)$, where m *is* the number of repetitions;k is the number of factors in the regression equation.

To assess the significance of the obtained regression coefficients, the observed value of Student's criterion is determined and compared with the tabulated value for the significance levelα = 0.5 for v_3 degrees of freedom, where $v_3 = m - 1$. The observed value of Student's criterion is calculated by the formula:

$$t_{CTj} = \frac{\alpha_j}{se_j}, \quad (8)$$

where a_j is the j-th coefficient of the linear regression equation; se_j is the error of the j-th coefficient of the regression equation (cell A2 - F2).

In accordance with the outlined methodology, experimental studies were carried out and the following dependences were obtained, shown in Figures 3-6.

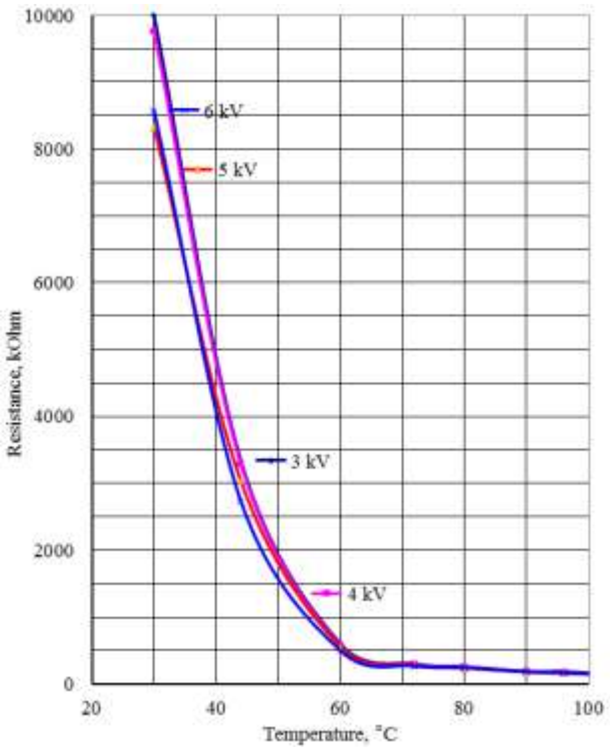

Fig. 3. Dependence of oil resistance on temperature at different electric field gradients

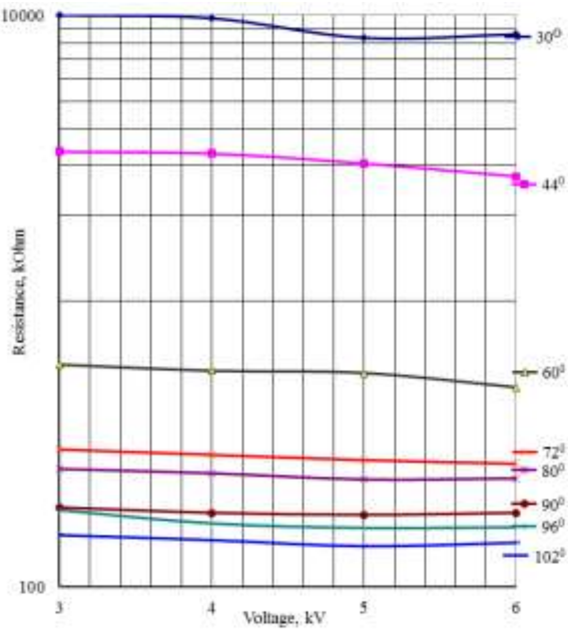

Fig. 4. Dependence of oil resistance on tension at different temperatures

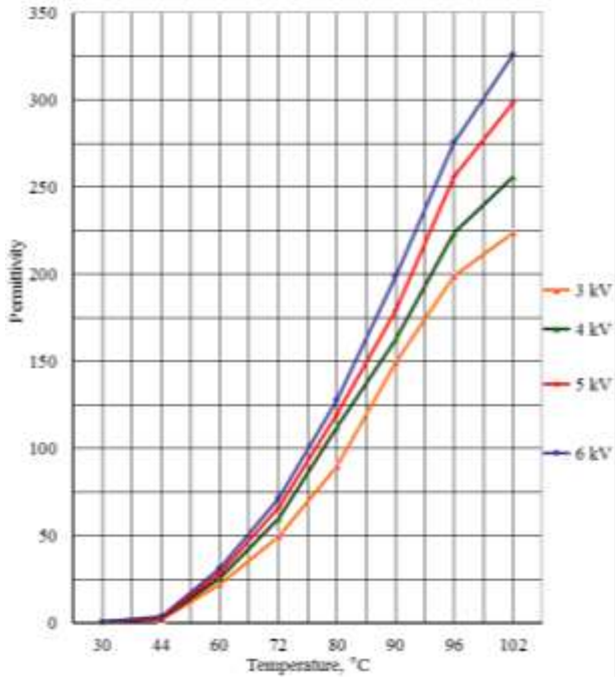

Fig. 5. Dependence of the dielectric constant of oil on temperature at different electric field gradients

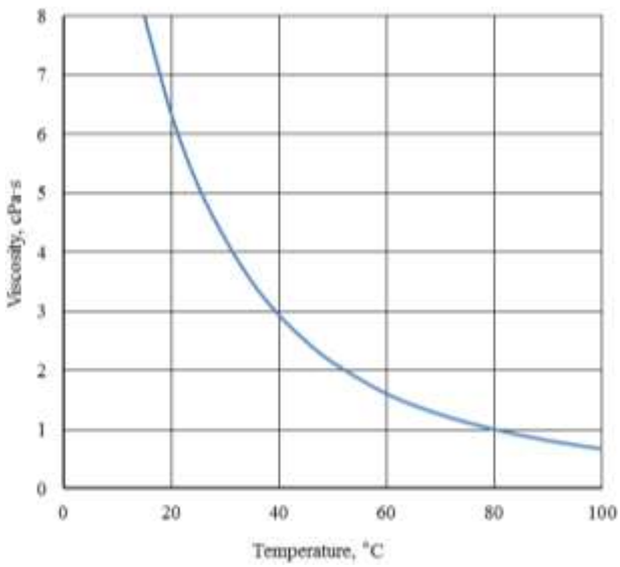

Fig. 6. Dependence of dynamic viscosity of sunflower oil temperature

It can be seen from the obtained graphs that the greatest influence on the oil parameters is its humidity and temperature. The voltage between the electrodes practically does not affect the electrical characteristics of the oil, which, in fact, confirms the theoretical provisions of electrical engineering.

As a result of processing of the obtained experimental dependences, they were approximated by the following polynomials

$$R = 0{,}0009 \cdot \theta^4 - 0{,}3175 \cdot \theta^3 + 0{,}03662 \cdot \theta^2 - 2{,}0733 \cdot \theta + 48 \, , \quad (9)$$

$$z = -0{,}0001 \cdot \theta^4 + 0{,}0214 \cdot \theta^3 - 0{,}3912 \cdot \theta^2 - 93{,}328 \cdot \theta + 4254{,}7 \, , \quad (10)$$

$$\varepsilon = -0{,}4064 \cdot \theta^4 + 5{,}7546 \cdot \theta^3 - 19{,}033 \cdot \theta^2 + 31{,}925 \cdot \theta - 18{,}863 \, . \quad (11)$$

As a result of processing the experimental data, a linear regression equation describing the DC resistance of oil depending on the influencing factors was obtained:

$$R = 32{,}71998 - 1{,}32089 \cdot \theta + 41{,}939865 \cdot \eta + 0{,}11472 \cdot \theta^2 -$$
$$- 44{,}634202 \cdot \eta^2 + 0{,}321065 \cdot \theta \cdot \eta \, , \quad (12)$$

Statistical analysis showed the following results:

- determinacy coefficient $R^2 = 0.981$;
- checking by Fisher's criterion confirmed the reliability of this value of the coefficient of determinacy (at the significance levelα = 0.5) - $F_{(NABL)} = 143.078 > F_{(TA)BL} = 143.078$;
- Student's test confirmed that the coefficients of the regression equation are significant (at the significance levelα = 0.5), the observed value was $t_{ST.NABL}$ = 3.67, which is greater than the tabulated value - $t_{ST(.TABL)}$ = *2.45*.

Thus, the obtained regression equation can be used to calculate the parameters of the cleaning process and ESP. After substituting the obtained dependence into the target function, the following calculated ones were obtained:

- inlet oil temperature - 40° C;
- oil moisture content before cleaning - 1.0%;
- the interelectrode distance is 10 mm;
- voltage - 3 kV;
- cleaning capacity - 76 kg/hour.

The data obtained experimentally were processed using a package of standard programmes Microsoft Excel to obtain regression equations of the form:

$$I = 0{,}0457 - 0{,}02424 \cdot U - 0{,}1858 \cdot b + 0{,}00387 \cdot \theta -$$
$$- 0{,}023 \cdot U \cdot b + 0{,}000411 \cdot U \cdot \theta -$$
$$- 0{,}00609 \cdot b \cdot \theta + 0{,}003632 \cdot U^2 + 0{,}21856 \cdot b^2 + 2{,}48 \cdot 10^{-5} \cdot \theta^2 \, , \quad (13)$$

$$T = -14{,}03 - 2{,}264 \cdot U + 112{,}528 \cdot b -$$
$$- 0{,}183 \cdot \theta - 10{,}598 \cdot U \cdot b - 0{,}0287 \cdot U \cdot \theta +$$
$$+ 0{,}137 \cdot b \cdot \theta - 0{,}744 \cdot U^2 - 20{,}239 \cdot b^2 + 0{,}00051 \cdot \theta^2 \, , \quad (14)$$

$$p = 0{,}00465 - 0{,}03032 \cdot U + 0{,}079788 \cdot b + 0{,}000746 \cdot \theta -$$
$$- 0{,}01477 \cdot U \cdot b + 0{,}00024 \cdot U \cdot \theta -$$
$$- 0{,}00166 \cdot b \cdot \theta + 0{,}00361 \cdot U^2 + 0{,}02052 \cdot b^2 + 4{,}37 \cdot 10^{-6} \cdot \theta^2 \, . \quad (15)$$

where I - current, A; T - cleaning time (time of oil staying in the electric field), hour; p - energy intensity of the cleaning process kWh/kg.

Statistical analysis of the obtained equations showed that all coefficients are significant with a significance level not worse than 0.01. The convergence of the experimental data and the data obtained in the form of regression equations was tested by the Cochran criterion. For this purpose, the null hypothesis of homogeneity of general dispersions was accepted. The calculated value of Cochran's criterion was $G_{KR.NABL} = 0.151$, which is less than the tabulated $G_{(KP)(.TABL)} = 0.3704$. Based on this, the null hypothesis of homogeneity of dispersions is not rejected, that is, the test confirmed the possibility of approximation of experimental data by regression equations.

The response surface for power consumption is presented in Figure 7. As can be seen from the obtained graph, the optimum ESP parameters are within the limits (oil temperature: 40...44°C; field gradient 4...5 kV).

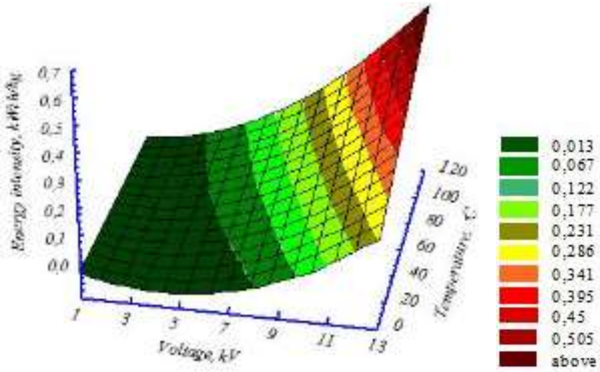

Fig. 7. Energy Capacity Voltage Temperature Response Function Surface

Analysis of the obtained equations showed that the optimum values of ESP parameters are located in the zone of minimum gap determining the breakdown voltage, which agrees well with the previously obtained theoretical results

To determine the minimum value of energy intensity and its corresponding voltage and temperature, the "Solution Search" function of the standard Microsoft Excel package was used.

4. Conclusion

Thus, the optimal parameters of the electrostatic precipitator by the criterion of energy consumption according to the obtained regression equations should be the following: voltage at the electrodes of the electrostatic precipitator U = 4.4 kV, interelectrode distance b = 0.01 m, oil temperature at the inlet θ = 42°C. The calculated energy consumption at these parameters is p= 12 W-h/kg.

The results of experimental studies slightly differ from the analytically obtained conclusions, namely, the optimal interelectrode distance in terms of energy consumption is greater than the minimum possible for technological reasons (0.01 m vs. 0.005 m). This can be explained by the fact that at small distances the oil bubbling near the negative electrode increases (which was observed visually during the experiment). The oil bubbling prevents the precipitation of impurities and increases the purification time. As a result, the energy consumption increases. It should be noted that the modern theory of electrophoresis does not allow analytically describe and account for this phenomenon, so experimental studies are justified.

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