

Для очистки води широкого застосування знайшли матеріали паперові фільтрувальні (МПФ), які легко піддаються утилізації. Основним недоліком абсолютної більшості фільтрувальних матеріалів, в тому числі і паперових, є їх схильність до біообростання. Даний недолік суттєво обмежує чи інколи навіть унеможливує використання фільтрувальних матеріалів та/чи сорбентів у певній сфері. У зв'язку з вищевикладеним, об'єктом даного дослідження став процес очистки води з використанням МПФ із незаражуючими властивостями на основі модифікованих целюлозних волокон та природного сорбенту палигорскіт, які можуть сорбувати механічні домішки, іони важких металів, ентеровіруси та бактерії.

Встановлено, що зразки модифікованих матеріалів паперових фільтрувальних із найвищою щільністю та найменшою товщиною та зразки із найменшою щільністю та найбільшою товщиною мають більшу фільтраційну та сорбційну здатності у порівнянні із зразками з середніми значеннями цих технологічних параметрів.

Набухання целюлозних волокон зменшує силу впливу композиційного складу досліджених зразків МПФ на їх фільтраційну здатність та збільшує силу впливу композиційного складу на сорбційну здатність цих МПФ.

Встановлено, що найкращі технологічні характеристики мають зразки, до складу яких було введено близько 40 % фосфорного ефіру целюлози.

Встановлено характер залежності швидкості процесу фільтрування від витрати очищуваної води, товщини, щільності та композиційного складу МПФ. Отримані математичні моделі представлені поліномом другого порядку та дозволяють враховувати не тільки технічні характеристики, але і вплив композиційного складу МПФ на швидкість процесу фільтрування очищуваної води. З досліджених параметрів найбільші сили впливу на швидкість процесу фільтрування при сталих тиску та концентрації забруднення мають відсотковий вміст сульфатної віскозної чи сульфатної біленої целюлози у папероутворюючій масі досліджених зразків та витрати очищуваної води. Запропоновані математичні моделі дозволяють також визначити необхідний композиційний склад для отримання МПФ з заданими властивостями

Ключові слова: модифіковані целюлозні волокна, ефективність очищення, вода, модернізовані матеріали паперові фільтрувальні, сорбційні та фільтрувальні властивості, математичні моделі, технологічний регламент експлуатації

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DEVELOPMENT OF MODERNIZED PAPER FILTERING MATERIALS FOR WATER PURIFICATION, ASSESSMENT OF THEIR PROPERTIES

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1. Introduction

The properties and the level of contamination of water strongly affect the health of people. In this connection, there is the need for water treatment and conditioning before using it with the application of appropriate materials and devices [1, 2].

In the period of global environmental security, the possibility of regeneration or disposal of filtering materials for devices that provide extraction of a wide range of pollutants from different media, primarily from water, is becoming especially important [2, 3].

Filtering paper materials (FPM) have gained wide use due to their high effectiveness, relative cheapness, and ease of recycling [4].

The application of filtering paper elements in special devices that ensure the maintenance of the highest purity of the treated medium is limited to resource, durability, filtration, sorption and other properties.

In connection with the need to ensure the highest purity of water in pharmaceutical and electronic industries, as well as the possibility of using the FPM for cleaning the air at nuclear power plants; in filter-ventilating systems of refuges, medical establishments, operational, production workshops

(fermentation departments) of the food and pharmaceutical industries, etc., there is a need for a mathematical model, with the help of which it would be possible to establish the compositional structure of the FPM, which would provide the samples with the required properties needed in each particular situation.

2. Literature review and problem statement

Contamination of water is one of the major risk factors for health, related to the environment, which necessitates the need for its proper purification before using [1, 2]. There is an urgent need for highly efficient sorbents, characterized by the simultaneous bactericidal action, for example, to clean drinking water, water for the pharmaceutical industry, or their use in medical practice [3].

At filtering different media, microbiological contaminations are absorbed by the materials with both the granulated and fibrous structure [4]. This not only maintains the viability, but also promotes the reproduction of micro-organisms [5]. That results in biofouling of sorbents and emission of microorganisms' waste products, and sometimes microorganisms themselves, into the filtrate [6]. Prevention of biofouling of filtering materials and, in particular, sorbents, remains a relevant scientific problem [7].

The use of activated carbon with the size of particles from 0.1 to 2,000 μm , impregnated with silver, in a complex method for deep water treatment and conditioning is well-known. The treated water is subjected to preliminary filtering [8]. Silver in the ionic and molecular forms moves into treated/conditioned water, contaminating it [9].

There are materials, obtained through processing the medium with metal salts, for example, a solution of silver salt. Bactericidal additive is on the surface of these materials either in the form of isolated ions, or in the form of complex compounds. These materials do not provide the necessary level of effectiveness of cleaning from colloidal particles and viruses, the size of which is within 10–30 μm [10]. The shortcomings also include the fact that the bactericidal properties of the used materials are determined by the ions of germicidal components of the used materials that during the process of filtering transfer to the purified medium, thus contaminating it [11]. To ensure the duration of retaining the germicidal properties of these materials, it is necessary to impregnate the carriers with the concentrated solutions of metals' salts. It is known that germicidal ions of metals at elevated concentrations are poisonous to humans [12].

Introduction of chemically modified natural sorbents and artificial synthetic components to the composition significantly alters the properties of FPM [13].

Processing of FPM with polymers based on guanidine may prevent the proliferation of pathogenic micro-organisms on their surface; however, it also changes other technological characteristics of the samples [14].

In regard to the foregoing, the modernization of the FPM composition, which would make it possible to obtain the required properties and to overcome the known shortcomings, is most appropriate. This would open the way to a wider use of modernized filtering paper materials in the pharmaceutical and electronic industries, at nuclear power plants, in filtering-ventilating systems of refuges, hospitals, medical establishments, operation rooms, production workshops (fermentation departments) of the food and

pharmaceutical industries, for additional purification of drinking water, etc.

However, the use of biocides for the purpose of biofouling prevention is complicated due to the change of the solidity, sorption, and filtration properties (which, in their essence, are crucial to the scope of application) of filtering paper materials, when they are used for purification process.

The research into the technological characteristics of the obtained FPM samples with disinfecting properties [14, 15], will make it possible to establish the impact of the compositional structure, first of all of paper-forming components, on the lifetime, sorption, filtration properties of the samples.

Development of mathematical models for calculation of the required compositional structure to obtain FPM with the assigned solidity, sorption and filtration properties makes it possible to substantiate the operating parameters of the technological regulations for manufacturing the samples with disinfecting properties with the use of polymers based on guanidine.

3. The aim and objectives of the study

The aim of this research is to assess the properties of the created modernized filtering paper materials for developing mathematical models that would make it possible to determine the compositional structure of filtering paper materials for obtaining the samples with assigned necessary characteristics.

To accomplish the aim, the following tasks have been set:

- to explore thickness, density and solidity of the created filtering paper materials in the wet state;
- to determine the dependence of filtering and sorption abilities of the studied samples of filtering paper materials on their compositional structure;
- to develop mathematical models that would make it possible to calculate the necessary compositional structure to obtain the FPM with the assigned properties.

4. Materials and methods to study filtering paper materials

To produce the modernized FPM, we used: sulfite viscose cellulose, sulfate bleached cellulose, natural sorbent – palygorskite (PAL).

Carboxymethylcellulose low-substituting (CMC-LS), phosphor ester of cellulose (PEC) and modernized FPM were obtained under laboratory conditions using the methods described below.

To obtain CMC-LS, sulfite viscose cellulose, crushed in the form of lumps with dimensions of 3 x 4 cm was subject to chemical modification. Cellulose was activated in cold at the temperature from 0 to 5 °C for 30 minutes by caustic soda, from which the solution with the content of 13 % of basic substance was prepared. Ratio (cellulose: alkali) is equal to 1:5.

Swollen cellulose was poured with the solution of monochloroacetic acid (MCAA) with the contents of the basic substance of 37 % to perform the reaction of O-alkylation. Module of bath by weight of the output cellulose MCAA is equal to 0.7. The resulting mass was heated in a water bath up to 70 °C and kept at this temperature for 30 minutes at periodic shaking. After this the mass was cooled to room temperature and was poured by acetic acid

solution with the content of the main substance of 5 % (1 dm³ of acid per 75 g of cellulose). After careful stirring, the mass was squeezed on the Buchner funnel and flushed with distilled water to the neutral reaction of flushing water (pH 6.0–7.0). The resulting product was dried in the air.

To obtain the PEC, sulfate viscose cellulose, crushed in the form of lumps with dimensions of 3 x 4 cm, was subjected to chemical modification.

To prepare the phosphorylating solution, orthophosphoric acid and carbamide were used. Cellulose was immersed into phosphorylating solution, preliminarily heated up to 80 °C and kept in it at constant stirring for 50–60 minutes.

Cellulose, impregnated with phosphorylating solution, was squeezed up to 3-fold increase in weight relative to the weight of the original cellulose and dried in the drying chamber up to the moisture content of 2–4 %, after which it was subjected to heat processing at a temperature of 150 °C for 1 hour.

After the thermal processing, the material was flushed with distilled water until a neutral reaction of flushing water and was dried in the air up to the moisture content of 6–10 %.

Phosphoric ether of cellulose in the ammonium form was obtained by the method described above. For its transfer to the N-form, the product was processed with 0.01 N hydrochloric acid solution with subsequent flushing with distilled water.

Laboratory samples of the modernized variants of filtering materials were produced on the unit LAKVO. Just before using for production of the modernized variants of filtering paper materials, all components of the compositional structure of the samples were crushed and dried in the drying chamber with forced convection at the temperature of 70±3 °C to the constant weight. Fibrous sorbents were ground by a laboratory disk mill of the MDL-01 model. Distilled water was used during manufacturing the samples.

To carry out research into the development and evaluation of the properties of the modernized FPM, laboratory samples weighing 200 g/m² having different compositional structure with different content of cellulose derivatives, the type of cellulose base, and existence of natural sorbent were prepared.

Introduction of both modified, and non-modified natural clay sorbents in the studied quantities to the composition of filtering paper materials does not cause changes in volume-spatial parameters of the paper-forming mass and the finished samples [14, 15], which can be explained by the location of this kind of sorbents in spaces between cellulose fibers.

Given the fact that PAL is a kind of clay natural minerals with the sorption properties, its content in the compositional structure was considered by more than 100 % of the paper-forming composition.

By 5 samples of FPM were produced based on sulfite viscose cellulose (SVC) and sulphate bleached cellulose (SBC).

The compositional structure of the samples is shown in Table 1.

Given the lack of the methods for determining the content of modified cellulose fibers as a part of filtering paper materials, as well as preliminary preparation of the components of the compositional structure of the samples, the content of each component in the corresponding prepared examined samples, were accepted according to Table 1.

The following characteristics of cellulose and modernized variants of FPM were explored: thickness, density, solidity in the wet state. Thickness was measured by using a thickness gauge with the set characteristics at specific pressure. Density was determined by calculation, based on the weight of the studied sample with the area of 1 m² and its

measured thickness that meets the international standards of the ISO 439-80 and ISO 534-80. Solidity in the damp state was determined based on the measurement of maximum force, which the sample withstands during stretching using the method of load at a constant rate.

Table 1

Compositional structure of the samples of filtering paper materials based on sulfite viscose cellulose and sulphate bleached cellulose

SVC-based		SBC-based	
FPM variant	Compositional structure	FPM variant	Compositional structure
1.1	100 % SVC	2.1	100 % SBC
1.2	30 % SVC + 70 % CMC-LS	2.2	30 % SBC + 70 % CMC-LS+PAL*
1.3	30 % SVC + 70 % FEC	2.3	30 % SBC + 70 % FEC
1.4	40 % SVC + 60 % FEC	2.4	40 % SBC + 60 % FEC
1.5	50 % SVC + 50 % FEC	2.5	50 % CBS + 50 % FEC

Note: * – given that SVC, SBC, FEC and CMC-LS belong to paper-forming components, and PAL belongs to natural clay minerals that do not change the volume-spatial parameters of paper-forming mass and finished samples, sorbent in compositional structure was considered by more than 100 % of the paper-forming composition

Filtering and sorption characteristics were determined by filtering the model solution of ferric chloride at the temperature of 20±2 °C, with the concentration of total iron in the original solution of 0.63±0.02 mg/dm³ through the appropriate FPM sample of the area of 39.57 cm² under the pressure of 500 mm of water column.

5. Results of research of filtering paper materials and filtering-sorption processes with their use

5.1. Technological characteristics of resulting samples

The data on thickness, density and solidity in the wet state of the resulting samples are given in Table 2.

Table 2

Technological characteristics of the materials of filtering paper materials based on sulfite viscose cellulose and sulphate bleached cellulose*

SVC-based				SBC-based			
FPM variant	Thickness, μm	Density, g/cm ²	Solidity in wet state, N	FPM variant	Thickness, μm	Density, g/cm ²	Solidity in wet state, N
1.1	450	0.47	4.0	2.1	390	0.56	5.4
1.2	500	0.43	1.7	2.2	425	0.52	3.0
1.3	440	0.50	3.8	2.3	423	0.51	4.6
1.4	432	0.50	3.8	2.4	420	0.51	3.7
1.5	434	0.48	3.9	2.5	405	0.51	4.5

Note: * – relative error of determining thickness does not exceed 7.5 %, density – 8.5 %

5.2. Filtering and sorption capabilities of the studied samples of filtering paper materials of different compositional structure

The established averaged data of the filtering and sorption capability of the FPM variants depending on the type of cellulose base are given in Table 3.

Table 3

Averaged filtration and sorption capability of filtering paper materials, depending on the type of cellulose base

SVC-based				SBC-based			
FPM variant	Amount of filtered water, dm ³	Rate of filtering, dm ³ /cm ² .min	Iron sorption, %	FPM variant	Amount of filtered water, dm ³	Rate of filtering, dm ³ /cm ² .min	Iron sorption, %
1.1	1	3.6	55.1	2.1	1	1.14	75.5
	2	0.7	79.9		2	0.2	84.9
1.2	1	5.9	87.0	2.2	1	5.0	69.2
	2	1.2	88.9		2	1.1	81.0
1.3	1	7.5	34.4	2.3	1	0.7	81.7
	2	6.6	40.4		2	0.35	88.0
1.4	1	0.47	41.6	2.4	1	1.7	81.2
	2	0.16	92.2		2	0.5	100.0
1.5	1	0.40	62.6	2.5	1	0.7	82.5
	2	0.23	93.6		2	0.35	89.0

5.3. Mathematical models for calculation of the required compositional structure of paper-forming mass for obtaining samples of filtering paper materials with assigned properties

In the process of filtering liquids, the significant role is played by the rate of filtering, which in turn depends on the nature of the feed of the treated disperse system, thickness and density of filtration element. To construct a mathematical model for determining the rate of filtration depending on the amount of filtered fluid, thickness and density of a paper filter, content of SVC/SBC in the paper-forming mass at constant pressure in the form of second-order polynomial, the empirical studies of the full factorial experiment were carried out. The levels of factors variation are given in Table 4.

Table 4

Levels of factor variation

Factors	Factor designation	$x_i^*=-1.68$	$x_i=-1$	$x_i=0$	$x_i=1$	$x_i^*=1.68$
Amount of filtered fluid Q , dm ³	x_1	0.66	1	1.5	2	2.34
Thickness of a paper filter δ , μm	x_2	400	420	450	480	500
Density of a paper filter ρ , g/cm ²	x_3	0.4	0.42	0.45	0.48	0.5
Content of SVC/SBC s , %	x_4	0	30	50	80	100

Encoding of factors will be performed through transformation:

$$x_j = \frac{\tilde{x}_j - \tilde{x}_{j0}}{I_j}, \tag{1}$$

where x_j is the encoded value of factor; \tilde{x}_j is the natural value of factor; \tilde{x}_{j0} is the natural value of basic level; I_j is the variation interval; j is the number of factor.

We will display the matrix of plan calculated from the transformation formula and corresponding results of the experiment (Table 5).

Table 5

Matrix of plan and results of the experiment

No. of experiment	Encoded value of factors in the experiment					
	\tilde{x}_1	\tilde{x}_2	\tilde{x}_3	\tilde{x}_4	For SVC	For SBC
					v , dm ³ /cm ² .min	
1	-1	-1	-1	1	1.88	1.72
2	1	-1	-1	1	1.32	1.12
3	-1	1	-1	1	1.55	1.52
4	1	1	-1	1	1.56	1.6
5	-1	-1	1	1	1.84	1.64
6	1	-1	1	1	1.09	0.86
7	-1	1	1	1	1.1	0.89
8	1	1	1	1	0.95	0.72
9	-1	-1	-1	-1	1.47	1.47
10	1	-1	-1	-1	0.95	0.75
11	-1	1	-1	-1	1.15	0.96
12	1	1	-1	-1	1.21	1.1
13	-1	-1	1	-1	2.15	2.15
14	1	-1	1	-1	1.39	1.15
15	-1	1	1	-1	1.4	1.17
16	1	1	1	-1	1.25	0.99
17	1.68	0	0	0	0.75	0.74
18	-1.68	0	0	0	1.34	1.37
19	0	1.68	0	0	0.83	0.88
20	0	-1.68	0	0	1.26	1.48
21	0	0	1.68	0	1.1	1.14
22	0	0	-1.68	0	1.15	1.21
23	0	0	0	1.68	2.01	1.38
24	0	0	0	-1.68	1.88	1.4
25	0	0	0	0	1.03	1.05
26	0	0	0	0	1.0	1.1
27	0	0	0	0	1.05	1.16
28	0	0	0	0	1.15	1.2
29	0	0	0	0	1.12	1.03
30	0	0	0	0	1.04	1.17
31	0	0	0	0	1.1	1.08

In this case, the mathematical model for the full four-factor experiment with the interaction effect takes the form:

$$y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_4 \cdot x_4 + b_{12} \cdot x_1 \cdot x_2 + b_{13} \cdot x_1 \cdot x_3 + b_{14} \cdot x_1 \cdot x_4 + b_{23} \cdot x_2 \cdot x_3 + b_{24} \cdot x_2 \cdot x_4 + b_{34} \cdot x_3 \cdot x_4 + b_{11} \cdot x_1^2 + b_{22} \cdot x_2^2 + b_{33} \cdot x_3^2 + b_{44} \cdot x_4^2. \tag{2}$$

The coefficients of the model are calculated from formula:

$$b_j = \frac{\sum_{i=1}^N x_{ji} \cdot y_i}{N}, \tag{3}$$

where $j=0, 1, 2, \dots, k$; N is the number of performed experiments ($N=31$).

Coefficients of the model (2), calculated from formula (3), are:

– for SVC:

$$\begin{aligned} b_0 &= 1,1; \quad b_1 = -0,18; \quad b_2 = -0,13; \\ b_3 &= -0,0004; \quad b_4 = 0,03; \\ b_{12} &= 0,16; \quad b_{13} = -0,06; \quad b_{14} = -0,0015; \quad b_{23} = -0,11; \\ b_{24} &= -0,06; \quad b_{34} = -0,18; \quad b_{11} = 0,01; \\ b_{22} &= 0,01; \quad b_{33} = 0,034; \quad b_{44} = 0,34. \end{aligned}$$

– for SBC:

$$\begin{aligned} b_0 &= 1,11; \quad b_1 = -0,2; \quad b_2 = -0,13; \quad b_3 = -0,01; \quad b_4 = 0,04; \\ b_{12} &= 0,16; \quad b_{13} = -0,06; \quad b_{14} = -0,0015; \\ b_{23} &= -0,11; \quad b_{24} = -0,06; \\ b_{34} &= -0,18; \quad b_{11} = 0,01; \\ b_{22} &= 0,014; \quad b_{33} = 0,012; \quad b_{44} = 0,112. \end{aligned}$$

Variance S_y^2 of reproduction is determined by the results of research in the center of the plan. Variances that characterize errors in determining coefficients of regression equation, according to [16] at $\kappa = 4$ are:

– for SVC:

$$\begin{aligned} S^2\{b_0\} &= 0,0526; \quad S^2\{b_1\} = 0,0299; \\ S^2\{b_{ii}\} &= 0386; \quad S^2\{b_{ii}\} = 0288; \end{aligned}$$

– for SBC:

$$\begin{aligned} S^2\{b_0\} &= 0,0629; \quad S^2\{b_1\} = 0358; \\ S^2\{b_{ii}\} &= 0464; \quad S^2\{b_{ii}\} = 0,0345. \end{aligned}$$

After checking coefficients by the Student criterion (at 5 % level of significance and number of degree of freedom $f = 5$), it was found that coefficients b_3 ; b_{14} ; b_{11} ; b_{22} (for SVC) and b_3 ; b_{14} ; b_{11} ; b_{22} ; b_{33} (for SBC) are smaller than confidence interval, that is why they can be recognized as statistically insignificant and excluded from the model (2).

After substituting the found coefficients in equation (2), we will obtain the following ratio:

– for SVC:

$$y = 1,1 - 0,18 \cdot \tilde{x}_1 - 0,13 \cdot \tilde{x}_2 + 0,03 \cdot \tilde{x}_4 + 0,16 \cdot \tilde{x}_1 \cdot \tilde{x}_2 - 0,06 \cdot \tilde{x}_1 \cdot \tilde{x}_3 - 0,11 \cdot \tilde{x}_2 \cdot \tilde{x}_3 - 0,06 \cdot \tilde{x}_2 \cdot \tilde{x}_4 - 0,18 \cdot \tilde{x}_3 \cdot \tilde{x}_4 + 0,034 \cdot \tilde{x}_3^2 + 0,34 \cdot \tilde{x}_4^2; \tag{4}$$

– for SBC:

$$y = 1,11 - 0,2 \cdot \tilde{x}_1 - 0,13 \cdot \tilde{x}_2 + 0,04 \cdot \tilde{x}_4 + 0,16 \cdot \tilde{x}_1 \cdot \tilde{x}_2 - 0,06 \cdot \tilde{x}_1 \cdot \tilde{x}_3 - 0,11 \cdot \tilde{x}_2 \cdot \tilde{x}_3 - 0,06 \cdot \tilde{x}_2 \cdot \tilde{x}_4 - 0,18 \cdot \tilde{x}_3 \cdot \tilde{x}_4 + 0,112 \cdot \tilde{x}_4^2. \tag{5}$$

Verification of the hypothesis of adequacy of models (4) and (5) by Fisher criterion at a 5 % level of significance and the numbers of degrees of freedom of the adequacy variance

$$f_{ad} = N - k' - (n_0 - 1) = 31 - 14 - (7 - 1) = 11$$

and reproduction variance

$$f_y = n_0 - 1 = 7 - 1 = 6$$

showed that the resulting models are adequate, since the calculation value of the criterion is lower than the tabular value

$$F_{cal} = 2,84 < F_T(0,05; 11; 6) = 3,09 \text{ (for SVC)}$$

and

$$F_{cal} = 2,45 < F_T(0,05; 11; 6) = 3,09 \text{ (for SBC)}.$$

In equations (4)–(5) variable values \tilde{x}_1 , \tilde{x}_2 , \tilde{x}_3 , \tilde{x}_4 are encoded magnitudes:

$$\begin{aligned} \tilde{x}_1 &= \frac{Q - 1,5}{0,5}; \quad \tilde{x}_2 = \frac{\delta - 450}{30}; \\ \tilde{x}_3 &= \frac{\rho - 0,45}{0,03}; \quad \tilde{x}_4 = \frac{c - 50}{30}, \end{aligned} \tag{6}$$

where Q is the amount of filtered fluid, dm^3 ; δ is the thickness of a paper filter, μm ; ρ is the density of a paper filter, g/cm^2 ; c – content of SVC/SBC, %.

For the convenience of calculations, mathematical model (4), (5) will be transformed into natural magnitude:

– for SVC:

$$\begin{aligned} v1 &= -15,1 - 3,4 \cdot Q + 0,04 \cdot \delta + 36,4 \cdot \rho + \\ &+ 0,08 \cdot c + 0,011 \cdot Q \cdot \delta - 4 \cdot Q \cdot \rho - 0,12 \cdot \delta \cdot \rho - \\ &- 7 \cdot 10^{-5} \cdot \delta \cdot c - 0,2 \cdot \rho \cdot c + 37,8 \cdot \rho^2 + 3,7 \cdot 10^{-4} \cdot c^2; \end{aligned} \tag{7}$$

– for SBC:

$$\begin{aligned} v2 &= -22,4 - 3,4 \cdot Q + 0,04 \cdot \delta + 70 \cdot \rho + \\ &+ 0,11 \cdot c + 0,011 \cdot Q \cdot \delta - 4 \cdot Q \cdot \rho - 0,12 \cdot \delta \cdot \rho - \\ &- 7 \cdot 10^{-5} \cdot \delta \cdot c - 0,2 \cdot \rho \cdot c + 1,2 \cdot 10^{-4} \cdot c^2, \end{aligned} \tag{8}$$

$v1$ is the rate of filtering the treated water through SVC-based FPM, dm^3/cm^2 ;

$v2$ is the rate of filtering the treated water through SBC-based FPM, dm^3/cm^2 .

Using mathematical models (7), (8), it is possible to determine the rate of filtering at constant pressure of the

treated water and to select the necessary characteristics of filtering paper materials to solve the relevant problems.

The dependence of the rate of filtering of the model ferric chloride solution under pressure of 500 mm of water column at percentage content of SVC or SBC in the paper-forming mass of the studied samples is shown in Fig. 1, 2.

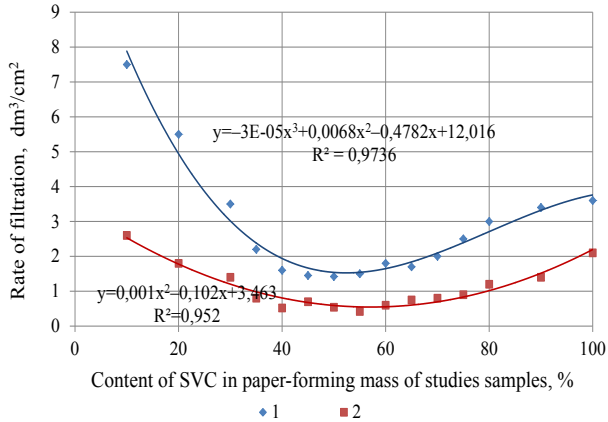


Fig. 1. Dependence of the rate of filtration through FPM on SVC content: 1 – at $Q=1 \text{ dm}^3$; 2 – at $Q=2 \text{ dm}^3$

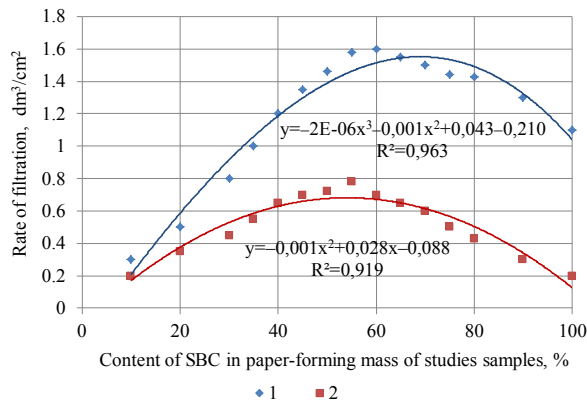


Fig. 2. Dependence of the rate of filtration through FPM on SBC content: 1 – at $Q=1 \text{ dm}^3$; 2 – at $Q=2 \text{ dm}^3$

The dependence of iron sorption of the model solution (original concentration is $0.63 \pm 0.02 \text{ mg/dm}^3$) on the percentage content of SVC or SBC in the paper-forming mass of the samples is shown in Fig. 3, 4.

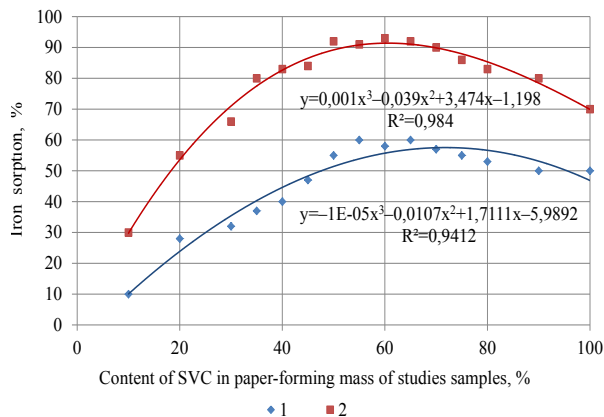


Fig. 3. Dependence of iron sorption by FPM on SVC content: 1 – at $Q=1 \text{ dm}^3$; 2 – at $Q=2 \text{ dm}^3$

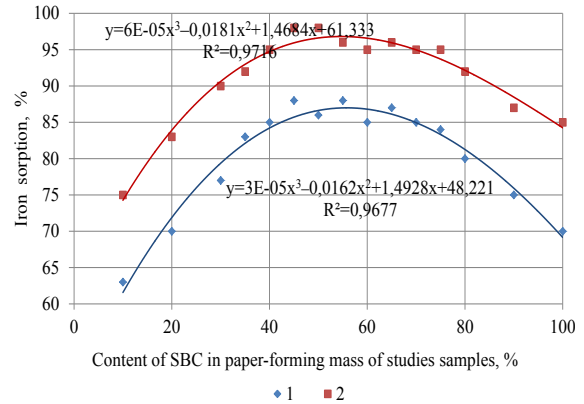


Fig. 4. Dependence of iron sorption by FPM on SBC content: 1 – at $Q=1 \text{ dm}^3$; 2 – at $Q=2 \text{ dm}^3$

Graphic dependences of filtration and sorption capabilities of the FPM variants on their thickness and density are shown in Fig. 5, 6 (for the SVC-based FPM) and Fig. 7, 8 (for the SBC-based MPF).

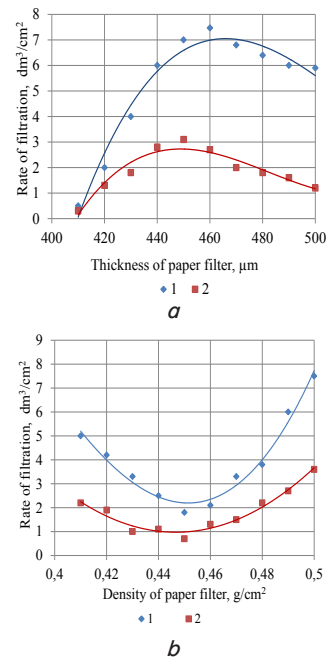


Fig. 5. Dependence of the rate of water filtering through SVC-based FPM: *a* – on thickness; *b* – on density; 1 – at $Q=1 \text{ dm}^3$; 2 – at $Q=2 \text{ dm}^3$

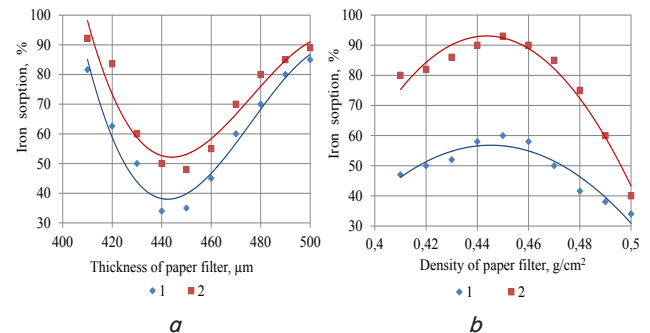


Fig. 6. Dependence of iron sorption through SVC-based FPM: *a* – on thickness; *b* – on density; 1 – at $Q=1 \text{ dm}^3$; 2 – at $Q=2 \text{ dm}^3$

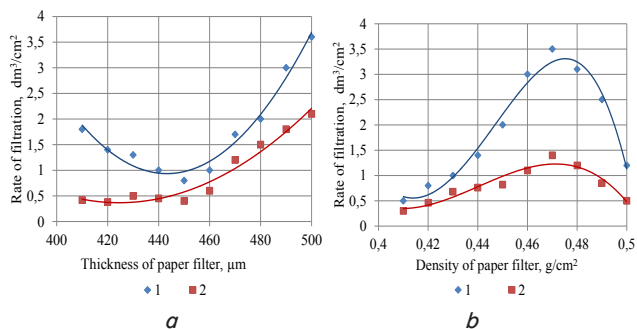


Fig. 7. Dependence of the rate of water filtering through SBC-based FPM: *a* – on thickness; *b* – on density; 1 – at $Q=1\text{ dm}^3$; 2 – at $Q=2\text{ dm}^3$

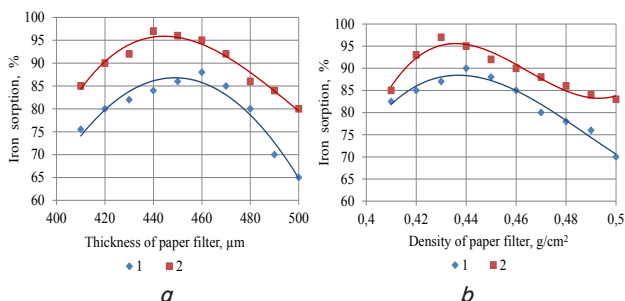


Fig. 8. Dependence of iron sorption through SBC-based FPM: *a* – on thickness; *b* – on density; 1 – at $Q=1\text{ dm}^3$; 2 – at $Q=2\text{ dm}^3$

6. Discussion of results of studying the filtering paper materials

Conducted research made it possible to identify the dependence of filtering and sorption capabilities of filtering paper materials on their compositional structure, thickness and density.

The same character of the obtained curves (Fig. 1, 2) at different amount of filtered water (Q) makes it possible to separate the influences that are conditionally different by nature on the rate of filtering through the studied samples of filtering paper materials, specifically: those related to the introduction of certain components to the composition of the sample of filtering paper materials and those related to the phenomenon of cellulose fibers' swelling. From the standpoint of modern science, in order to reduce the time and number of observations, interpolation of patterns obtained under the aggravated conditions, on the process in general is quite acceptable. Thus, in terms of detecting the influence of these components on the rate of filtering rather than the results of their interaction with the purified medium, the data that are at the basis of plotting curve 1 are more significant, while curve 2 can be considered the one that was changed by the information noise. This statement is also clear and fair for the other experimentally established dependences.

The analysis of the obtained data on physical and mechanical parameters of filtration and sorption characteristics of the modified FPM made it possible to establish the following:

- the control samples that included either sulfate bleached cellulose, or only sulfite viscose cellulose, have the best solidity characteristics in the wet state – 5.4 H and 4.0 H, respectively;

- the FPM samples from sulfite cellulose are characterized by lower values of density, solidity in the wet state, effectiveness of cleaning from iron ions, and by higher values of the rate of filtering than similar samples from sulphate cellulose;

- the use of CMC-LS and natural sorbent PAL in the MPF composition leads to a decrease in density, solidity in the wet state, an increase in the rate of filtering, however, the value of effectiveness of cleaning from ions of iron Fe^{+3} is higher for the variants based on sulfite cellulose;

- compositions of additives of phosphorus ester of cellulose (FEC) are characterized by a decrease in density, solidity in the wet state, a decrease in the rate of filtering for the samples based on sulphate bleached cellulose, or an increase for the samples based on sulfite cellulose;

- the best filtration ability is characteristic of the samples, the paper-forming composition of which includes 70 % of phosphoric ester of cellulose and 30 % of sulfite viscose cellulose (the rate of filtering is 6.6–7.5 dm^3/cm^2 per minute) or 70 % of carboxymethylcellulose low-substituted and 30 % of sulfate bleached cellulose (the rate of filtering is 1.1–5.0 dm^3/cm^2 per minute);

- introduction of FEC to the composition of the MPF improves the effectiveness of iron ions' sorption;

- the best sorption capacity in relation to iron is typical of the samples, the composition of paper-forming components of which includes 60 % of phosphoric ester of cellulose and 40 % of sulfate bleached cellulose (81.2–100 %) or 50 % of phosphoric ester of cellulose and 50 % of sulfite viscose cellulose (62.6– 92.3 %).

It was found that the samples with the highest density and the lowest thickness and the samples with the lowest density and the highest thickness have better filtration and sorption capabilities than the samples with medium values of density and thickness. This suggests that the filtering and sorption characteristics are also influenced by the spatial location of fibrous sorbents in the filtering layer of the FPM, which may be associated with the phenomenon of cellulose fibers' swelling in the wet state.

Changes in characteristics of filtering paper materials after swelling of cellulose fibers that are the part of their composition should be taken into consideration in the technological regulations of operation for the devices on their basis. The desirability of permanent pressure of the treated fluid should also be taken into account, which is true for all currently known water treatment devices.

The variants of filtering paper materials, first of all, 1.1 (as control samples); 1.4; 1.2 (as control samples); 2.4 are the most promising for the further research.

7. Conclusions

1. Introduction of phosphorus ether of cellulose to the composition of filtering paper materials changes their thickness, density and solidity in the wet state. The nature of the changes depends on the type of the cellulose base of the samples: sulfite viscose cellulose or sulfate bleached cellulose. The samples, into the composition of which we introduced about 40 % of phosphorus ester of cellulose have the optimal combination of technological characteristics.

2. Introduction of the studied cellulose derivatives to the composition of the modified filtering paper materials leads to various influences on the filtration and sorption

capabilities of the samples, which primarily depends on the type of their cellulose base. Swelling of cellulose fibers decreases the power of influence of the compositional structure of the studied samples of filtering paper materials on their filtration ability and increases its influence on their sorption capacity. The use of the natural non-modified palygorskite in the composition of filtering paper materials does not increase their sorption capability and capacity in relation to iron, due to which the use of natural clay sorbents without their previous chemical modification can be considered inappropriate. The problem of expediency of modified natural sorbents' introduction to the composition of filtering paper materials requires subsequent studying.

3. The developed mathematical models make it possible to determine the rate of the filtration process at constant pressure and concentration of contamination depending on

the consumption of filtered water, thickness, density and compositional structure of filtering paper materials. Among the studied parameters, the percentage content of sulfite viscose cellulose or sulfate bleached cellulose in the paper-forming mass of the studied samples and consumption of the purified water have the highest force of influence at the rate of the filtration process at constant pressure and contamination concentration. The proposed mathematical models make it possible to determine the necessary compositional structure to receive the FPM with assigned properties.

4. During manufacturing filtering paper materials with the necessary assigned properties and their use, it is necessary to take into consideration the influence of swelling of cellulose fibers on their production characteristics, which must be displayed in technological regulations for operation of devices on their basis.

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