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ESTABLISHING A DEPENDENCE OF THE EFFICIENCY OF LOW-PRESSURE REVERSE OSMOTIC MEMBRANES ON THE LEVEL OF WATER MINERALIZATION

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This paper has established the dependence of the effectiveness of the reverse-osmotic low-pressure membranes Filmtec TW30-1812-50 on the initial concentrations of sulfate and sodium chloride in the range of 20–1000 mg/dm^3 at the degrees of permeate selection of 1–90 % with the use of pressure of 3.6–10.0 atm. The dynamics of increasing the content of sulfates and chlorides in concentrates with an increase in the degree of permeate selection, selectivity, productivity, and filtration coefficient of the membrane have been determined. The conditions for calculating the membrane performance depending on the working pressure for sodium sulfate and sodium chloride have been defined.

It is shown that the concentrations of sulfates and chlorides in permeates depend on their initial concentration in solutions and increase both with an increase in the initial concentration and with an increase in the degree of permeate selection. The latter factor is quite significant at the initial concentrations of chlorides and sulfates at a concentration of 1000 mg/dm^3. The productivity of the membrane increases with a decrease in the salt content in water and decreases as the degree of permeate selection increases, which leads to an increase in the concentration of salts in the premembrane space.

The selectivity of the membrane increases with increasing concentration of sodium sulfate and sodium chloride solutions in solutions, despite a certain increase in salt concentrations in permeates. For solutions of Na_2SO_4 and NaCl (20–1000 mg/dm^3) at their reverse-osmotic desalting on the membrane, the filtration coefficients have constant values. For these initial concentrations, the filtration coefficient for Na_2SO_4 is 3.4–3.8 dm^3/(m^2·atm), and for NaCl – 2.6–3.2 dm^3/(m^2·atm). The data reported here allow us to conclude about the permissible level of mineralization, at which it is advisable to use reverse-osmotic low-pressure membranes. It is shown that an increase in the concentration of salts in concentrates leads to an increase in osmotic and working pressures

Keywords: water demineralization, reverse osmosis, low-pressure membranes, permeate, concentrate

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1. Introduction

The issues related to water softening and desalting occupy a significant place both in water treatment technologies and in wastewater treatment techniques. This is due to the constant increase in the mineralization of natural waters due to anthropogenic impact and the need to use mineralized water due to a decrease in the number and capacity of fresh water supply sources. A significant part of natural water bodies is polluted by mineral impurities due to controlled and uncontrolled discharge of mine waters, unplanned losses of highly mineralized reservoir waters in oil and gas production. A high level of mineralization is observed, for example, in the waters of the Dniester, Dniprobuzhansky estuaries, in soil and groundwater of coastal areas. Often, water treatment stations with centralized water supply, in local water supply systems do not provide the required level of water demineralization. Therefore, to improve the quality of water by the population in everyday life, membrane installations for water purification are widely used. The effectiveness of the use of such installations depends largely on the characteristics of the water and the selected type of equipment. Therefore, it is a relevant task to assess the effectiveness of water purification when using local installations in everyday life, to determine the feasibility of their use depending on the characteristics of tap or artesian water that needs to be cleaned.

2. Literature review and problem statement

Natural waters with high mineralization are most often, along with hardness ions and bicarbonates [1], contaminated with chlorides, sulfates [2], and sodium cations. When preparing water for industrial needs, drinking water, and when cleaning tap water in everyday life, ion exchange installations are often used [3]. However, the use of such installations is limited to sodium-cation filters in the processes of deferrization, demanganization, softening, and desalting of water [4]. In this case, the problem of regeneration of ion exchange filters is easily solved by simple treatment with sodium chloride solutions. In the case of complete desalting of water using cation exchangers and anionites, it is necessary to use sequentially acid and alkaline regeneration of cationites and anionites, respectively. This is unacceptable at home, and is accompanied by the accumulation and processing of acid-base effluents in the industry.

It is much easier to implement the processes of baromembrane desalination [5]. In the case of low mineralization of water and low chloride content, it is better to use nanofiltration [6]. These processes are characterized by high productivity, the use of relatively low pressures, and lower energy consumption [7] compared to reverse osmosis [8]. However, the issue of the deposition of scale (sediments) on membranes remains unresolved [9]. An option to overcome the corresponding difficulties may be a preliminary stabilization treatment of water in front of membrane installations. In [10], the results of studies of pretreatment of water on a weakly-acidic cation exchange are given; reliable protection of membranes from carbonate deposits is provided. This approach is also effective when using reverse osmosis.

If there are chlorides, sodium ions, and other single-charge ions in water in significant concentrations, it is necessary to use reverse osmosis [11, 12]. This method is now widely used both at water treatment stations [13], in local desalination plants, and in household water purification filters. However, the unresolved issue remains related to the problem of processing the resulting concentrates. Under domestic conditions, the resulting concentrates have a relatively low mineralization and are discharged into the sewage system. Nevertheless, at large water treatment stations with significant mineralization of water, the disposal of concentrates is an extremely difficult task. This, in fact, is a problem of both ion exchange [14] and electrodialysis [15, 16] during the desalting of water. In addition to the formation of concentrates, the issue with the electrodialysis desalting of water is the need for its deep softening [17]. An option to overcome the corresponding difficulties may be the modernization of the electrolyzer. Thus, in work [18], with changes in the design of the electrolyzer, the desalting of water by electrodialysis was achieved without first softening it. Electrodialysis of concentrated solutions [19, 20], along with reagent methods, is used for the processing of concentrates of ion exchange and baromembrane desalting of water [21, 22]. However, the most convenient and effective method of purification of tap water under domestic conditions is reverse osmosis, which makes it possible, along with water softening, to achieve its effective desalting.

It is advisable to use compact membrane modules for conditioning tap water and artesian water in everyday life. This application depends on the characteristics of water and the parameters of the process of its desalting. Therefore, it is important to determine the effectiveness of membrane cartridges depending on the conditions of use.

3. The aim and objectives of the study

The aim of this study is to determine the dependence of the effectiveness of low-pressure reverse osmosis membranes on the example of the Filmtec TW30-1812-50 membrane on the level of mineralization of aqueous solutions, the degree of selection of permeate at pressures of 3.6–10.0 atm.

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

– to assess the influence of the initial salt concentrations and the degree of permeate selection on the selectivity and productivity of the membrane at different pressures in the system;

– to establish the dependence of the dynamics of changes in salt concentrations in permeate and concentrate, osmotic and working pressure in the system on the degree of selection of permeate;

– to determine the required pressures in water desalting systems depending on the initial concentrations of sulfates and chlorides, provided that satisfactory membrane performance is achieved at a given desalting efficiency.

4. The study materials and methods

4. 1. Materials and equipment used in the experiment

The object of research in this work were the processes of reverse osmotic water purification, ensuring the production of high-quality water.

The hypothesis of the study assumed the following. Having experimentally determined the coefficients of reverse osmosis filtration based on salt solutions with known concentrations, it is possible to calculate the operating pressures in the system at specified levels of membrane productivity for purification of highly mineralized waters.

The scheme of installation for reverse osmotic water purification is shown in Fig. 1.

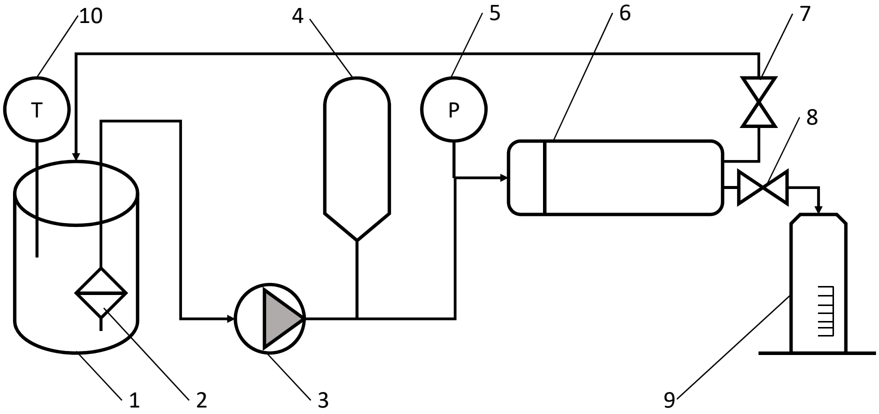

Fig. 1. Scheme of installation for reverse osmosis desalting of water: 1 – tank of the initial solution; 2 – water intake device; 3 – plunger pump – dispenser; 4 – hydraulic accumulator; 5 – pressure gauge; 6 – reverse osmosis module with a cartridge with the membrane Filmtec TW30-1812-50, 7, 8 – taps for adjusting, respectively, the consumption of concentrate and permeate, 9 – permeate receiver; 10 – thermometer

The reverse osmosis unit (6) used a cartridge with the reverse osmotic low-pressure membrane Filmtec TW30-1812-50 (USA).

Sodium sulfate solutions with sulfate concentrations of 20 mg/dm^3 were used as working solutions; 100 mg/dm^3 and 1000 mg/dm^3 and sodium chloride solutions with chloride concentrations of 20 mg/dm^3; 100 mg/dm^3; and 1000 mg/dm^3 in distilled water. The volumes of the working solutions ranged from 3 dm^3 to 11 dm^3.

To determine the pH of the medium, the laboratory ionometer I-160 MI was used; the change in the optical density of solutions was determined by the photoelectrocolorimeter KFK-2.

In this work, we used a laboratory unit, which makes it possible to determine the effectiveness of water purification, depending on the degree of selection of permeate. The return of the concentrate to the initial solution makes it possible to track the selectivity and productivity of the membrane with increasing salt concentration with an increase in the degree of selection of permeate. In everyday life, one can immediately set the required degree of selection of permeate but it is impossible to guess its optimal value. At low values of the degree of selection of permeate, a significant part of the water is lost with the concentrate discharged into the sewage system. If the required degree of permeate selection is exceeded at the selected pressure, the productivity and selectivity of the membrane decrease. The chosen research method makes it possible to determine the dependence of the productivity and selectivity of the membrane at a given pressure.

4. 2. Procedure for conducting an experiment on the desalting of solutions of sulfate and sodium chloride

We studied the processes of reverse osmosis desalination of water desalination as follows. A solution of sulfate or sodium chloride with a volume of 11 dm^3 or 3 dm^3 was placed in a container (1) (Fig. 1); then, using a pump (3), the solution was fed to the reverse osmosis module (6). To enable effective regulation of pressure in the system before the module (6), a hydraulic accumulator was used (4). The pressure in the system (P) was measured with a pressure gauge (5). Using a tap (7), the set pressure of the solution in the system was set in front of the module (6) from 3.6 atm to 10.0 atm. Through a tap (8), the permeate was sent to the permeate receiver (9). At the same time, the stopwatch recorded the time of the start of filtration and filling the receiver (9) with the required volume of permeate (500 cm^3 or 1000 cm^3). The pH, chloride or sulfate concentration, and temperature were determined in the working solution and permeate samples. Measurements in the working solution (concentrate) were carried out after taking a permeate sample of a given volume. With a working solution volume of 3 dm^3, 5 permeate samples with a volume of 500 cm^3 were taken. With a working solution volume of 11 dm^3, 10 samples of permeate with a volume of 1 dm^3 were taken.

The concentration of sulfates or chlorides in the concentrate during the selection of n samples of permeate (C_n) was calculated from the following formula:

$$C_{ni}=\frac{\left(C_0\cdot V_0-\sum_{i=1}^{n}\left(C_i\cdot V_i\right)\right)}{V_0-n\cdot V_i},\ \text{mg/dm}^3, \tag{1}$$

where C_{ni} is the concentration of chlorides or sulfates in the n^{th} sample of the concentrate, mg/dm^3;

C_0 – initial concentration of chlorides or sulfates in a working solution (mg/dm^3);

V_0 – the initial volume of working solution (dm^3);

n – the number of permeate samples taken;

i – permeate sample number (1, 2, 3, 4, 5......, n);

C_i – concentration of chlorides or sulfates in the i-th sample of permeate (mg/dm^3);

V_i – permeate sample volume (dm^3).

In permeate, the concentration of ions was determined analytically.

The selectivity of the membrane (R_{0i}, %) for sulfates or chlorides was calculated from the following formula:

$$R_{oi}=\frac{C_0-\quad{}_i}{C_0}\cdot 100,\ \%. \tag{2}$$

Membrane productivity (transmembrane flow rate) (j_i, $dm^3/(m^2\cdot h)$) for each sample of permeate taken was calculated from the following formula:

$$j_i=\frac{V_i}{S\cdot\Delta\tau_i},\ \text{dm}^3/(\text{m}^2\cdot\text{h}), \tag{3}$$

where j_i is the membrane productivity for the i-th sample, $dm^3/(m^2\cdot h)$;

V_i – volume of the i-th sample of permeate, 1 dm^3;

S – membrane area, m^2 ;

$\Delta\tau_i$ – the time of filtration of the solution with a volume of V_i, h.

The osmotic pressure of salt solutions was calculated as:

$$\pi=\varphi\cdot C\cdot R\cdot T,\ atm, \tag{4}$$

where C is the concentration of salt solution, mol/dm^3;

R – universal gas constant, R=8.31446261815 J/(mol·K);

T – absolute temperature, K;

φ *is* the osmotic coefficient.

$$\varphi=1+\alpha\cdot(m-1), \tag{5}$$

where α is the degree of electrolyte dissociation;

m – the number of ions formed during the dissociation of salt.

Working pressure in the system (P_{Pi}) after the selected i-th sample of permeate was calculated as:

$$P_{Pi}=P-\left(\pi_i-\pi_i'\right),\ \text{atm}, \tag{6}$$

where P_{Pi} is the working pressure in the system, atm;

P – pressure in the system, maintained at the selected level and controlled by a pressure gauge, atm;

π_i – osmotic pressure in the concentrate during the selection of the i-th sample of permeate, atm;

π' – osmotic pressure in the permeate of the i-th sample, atm.

The relationship between the working pressure (P_P), system pressure (P), and osmotic pressures (π, π') is described by formula (6). The pressure gauge measured the pressure in the system (P); the working pressure (P_P) was calculated based on the pressure in the system measured by the pressure gauge and the osmotic pressures in the concentrate (π) and permeate (π') depending on the concentration of salts in these media (4).

The filtering factor (l_{Pi}) for each sample taken was calculated from the following formula:

$$l_{Pi}=\frac{j_i}{P_{Pi}},\ (\text{dm}^3/(\text{m}^2\cdot\text{atm}). \tag{7}$$

Working pressure (P_{Pi}) after the selected i-th sample was also determined, based on the filtration coefficient, from the equation:

$$P_{Pi}=\frac{j_i}{l_{Pi}},\ \text{atm}. \tag{8}$$

The concentration of sulfates was determined by the photometric method with barium ions [23]; the concentration of chlorides was determined using the Mohr argentometric method [24].

5. Results of studies on desalting solutions of sulfate and sodium chloride on a low-pressure reverse osmotic membrane

5. 1. Evaluation of the influence of initial salt concentrations and the degree of permeate selection on the characteristics of the membrane

Evaluation of the influence of initial salt concentrations on the selectivity and productivity of the membrane.

The results on the efficiency of extraction of sulfates and chlorides from water on the low-pressure reverse osmotic membrane are shown in Fig. 2, 3.

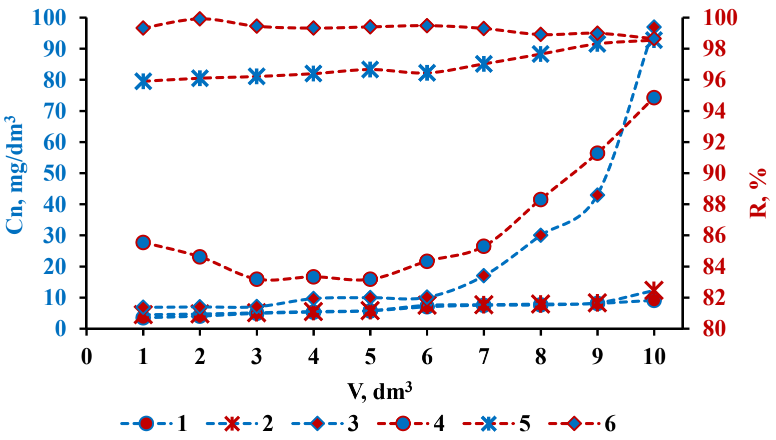

Fig. 2. Dependence of the concentration of sulfates in permeate (1–3), the selectivity of the membrane by sulfates (4–6) for solution volumes of 11 dm^3 (permeate sample volume, 1 dm^3) on the volume of the selected permeate at the initial concentration of sulfates in sodium sulfate solutions, mg/dm^3: 1, 4 – 20; 2, 5 – 100; 3, 6 – 1000; at the applied pressure 1, 2, 4, 5 – 3.6 atm; 3, 6 – 4.0 atm

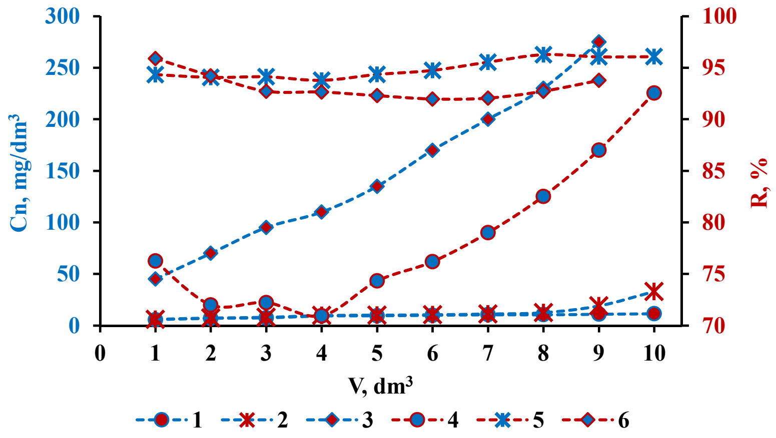

Fig. 3. Dependence of the concentration of chlorides in permeate (1–3) and the selectivity of the membrane by chlorides (4–6) at solution volumes of 11 dm^3 (permeate sample volume, 1 dm^3) on the volume of selected permeate when filtering sodium chloride solutions with initial chloride concentrations in initial solutions, mg/dm^3: 1, 4 – 20; 2, 5 – 100; 3, 6 – 1000; with applied pressure 1, 2, 4, 5 – 3.6 atm; 3,6 – 4.0 atm

Fig. 2 shows that the extraction of sulfates from the water on the selected membrane is quite effective if we take into consideration the processes of purification of drinking water under domestic conditions. The selectivity of the membrane exceeded 80 %, and as the concentrations in the initial solutions increased to 95–99 %. At the same time, in solutions with low initial concentrations of sulfates, an increase in selectivity was observed as the degree of permeate selection increased.

It should be noted that the concentration of sulfates in the permeate did not decrease but, to a certain extent, increased. At the initial concentration of sulfates 1000 mg/dm^3 with an increase in the degree of selection of permeate from 9 % to 90 %, the concentration of sulfates in permeate increased from 7 mg/dm^3 to 97 mg/dm^3 with a decrease in selectivity from 99.33 % to 98.65 %. This is despite the fact that the sulfate content in the concentrate has increased to about 7000 mg/dm^3.

Slightly different dependences were observed during desalting solutions of sodium chloride (Fig. 3). At the initial concentration of chlorides in the working solution of 20 mg/dm^3, the concentrations of chlorides in permeate reach 5.6–11.0 mg/dm^3, at a concentration of 100 mg/dm^3 – 6.0–33.0 mg/dm^3. And at the initial concentration of chlorides in the working solution of 1000 mg/dm^3 in permeate, as the degree of selection increases from 9.0 % to 82 %, the concentration of chlorides increases from 45 mg/dm^3 to 275 mg/dm^3. At the same time, working pressure in the system due to the increase in the osmotic pressure of the concentrate decreased to values close to 0 atm, therefore it was not possible to select the 10th sample of the permeate.

5. 2. Establishing the dependence of changes in salt concentrations and pressures in the system of reverse osmotic desalination

The peculiarity of membrane desalting of water when using reverse osmosis membranes is that with a selectivity of 80–99 %, with an increase in the degree of selection of permeate to 80–90 %, the salt content in concentrates increases significantly. This leads to an increase in the osmotic pressure of solutions and a decrease in the working pressure (Fig. 4, 5).

Fig. 4 shows that at a chloride concentration of 100–875 mg/dm^3 at a pressure in the system of 4 atm, the working pressure decreases from 3.5 atm to 2.9 atm. At the same concentrations of sulfates in water, the working pressure decreases from 3.6 atm to 3.2 atm.

At a chloride concentration of 1000–4420 mg/dm^3 (Fig. 5), the working pressure decreases from 3.195 atm to 0.441 atm, while for sulfates, in the same concentration range, the working pressure decreases from 3.554 atm to 2.064 atm. At a sulfate concentration of approximately 7000 mg/dm^3 , the osmotic pressure reaches 3.2 atm, and the working pressure decreases to 0.8 atm. For chlorides at a concentration of 7000 mg/dm^3 , the calculated osmotic pressure reaches 5.6 atm, which is higher than the pressure in the system of 4 atm. Therefore, at such concentrations of sodium chloride, filtration does not occur.

An increase in the concentration of salts in the working solution leads to a decrease in the working pressure, and therefore to a decrease in the productivity of the membrane (Fig. 6).

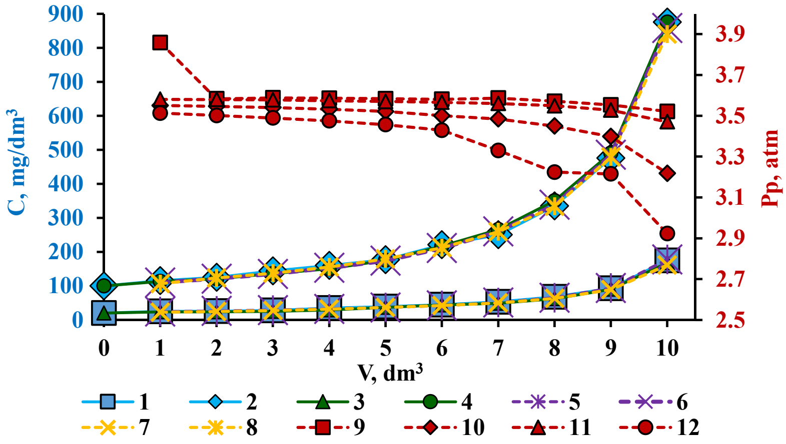

Fig. 4. Change in the measured (1–4) and calculated (5–8) concentration of sulfates (1, 2, 5, 6) and chlorides (3, 4, 7,8) in concentrates, working pressure (*Pp*) (9–12) at an external pressure of 3.6 atm depending on the volume of the selected permeate when filtering solutions 1, 2, 5, 6, 9, 10 – sodium sulfate, 3, 4, 7, 8, 11, 12 – sodium chloride with an initial concentration of sulfates and chlorides 1, 3, 5, 7, 9, 11 – 20 mg/dm^3 and 2, 4, 6, 8, 10, 12 – 100 mg/dm^3

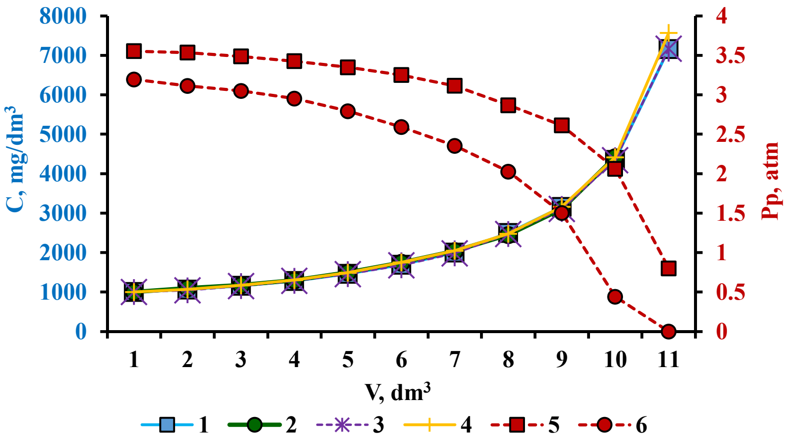

Fig. 5. Change in the measured (1, 2) and calculated (3, 4) concentration of sulfates (1, 3) and chlorides (2, 4) in concentrates, working pressure (*Pp*) (5, 6) depending on the volume at external pressure of 4 atm on the volume of samples of the selected permeate when filtering solutions 1, 3, 5 – sodium sulfate and 2, 4, 6 – sodium chloride with an initial concentration of sulfates and chlorides of 1000 mg/dm^3

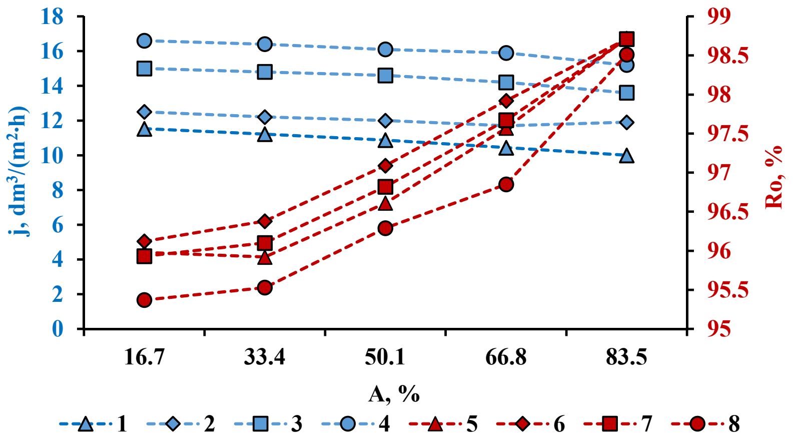

Fig. 6. Dependence of the productivity (*j*) (1–4) and selectivity R_o (5–8) of the membrane for the removal of sulfates at the initial volume of the solution of 3 dm^3 on the degree of selection of permeate (A, %) when filtering sodium sulfate solution $\left(\left[\mathrm{SO}_4^{2-}\right]=100\ \mathrm{mg/dm}^3\right)$ at pressures (*P*), atm: 1, 5 – 4; 2, 6 – 6; 3, 7 – 8; 4, 8 – 10

Fig. 6 shows that at concentrations of sodium sulfate (100–600 mg/dm^3) at a pressure in the system of 10 atm, there is a decrease in productivity from 16.6 dm^3/(m^2·h) to 15.2 dm^3/(m^2·h) with an increase in selectivity from 95.4 % to 98.5 %.

It is known that such a membrane indicator as productivity varies over a wide range depending on the applied pressure. More stable is the membrane filtration coefficient, which is calculated as the ratio of membrane performance to working pressure. This is confirmed by the data given in Fig. 7, 8.

Fig. 7, 8 demonstrate that the membrane Filmtec TW30-1812-50 is characterized not only by higher selectivity in sulfates, compared with chlorides, but also by higher productivity.

At the same time, in all the cases under consideration, there is a decrease in productivity with an increase in the concentration of solutions and with an increase in the selection of permeate.

It should be noted that each range of concentrations of solutions of sulfate and sodium chloride corresponds to close values of filtration coefficients. At the same time, there is a certain decrease in the filtration coefficient with a significant increase in salt concentration.

5. 3. Determining the required pressures in water desalting systems using reverse osmotic membranes

If we take into consideration the results given in this work, we can say that the membrane used meets the requirements for the quality of removal of sulfates and chlorides in a wide range of concentrations. Problems with the removal of salts are associated with a decrease in the performance of the membrane at low pressures. Based on the fact that at concentrations of sulfates and chlorides the filtration coefficients have stable values, the working pressure can be determined from equation (8).

Based on (4), we calculated the required pressure in the reverse osmosis system for certain concentrations of salts that can be achieved in the initial solution at a given degree of permeate selection. The results of the calculations are given in Tables 1, 2.

As can be seen from Table 1, to achieve a performance of 200 dm^3/day at an initial concentration of sulfates of 1–5 g/dm^3, working pressure (Pp) should be at the level of 8.172 atm, and the pressure in the system should not be lower than 12.632 atm.

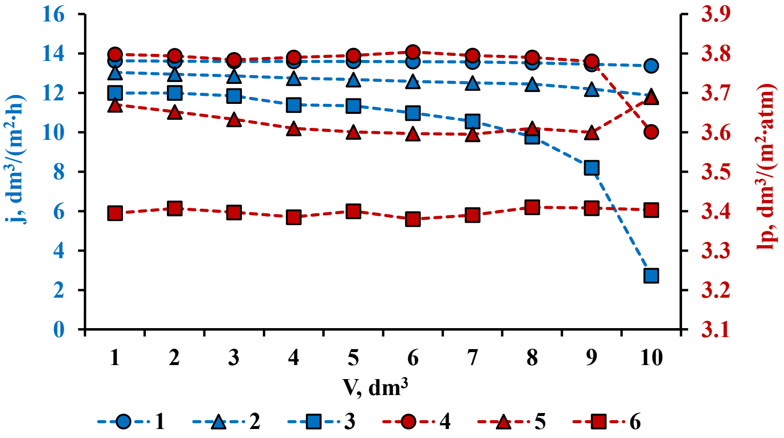

Fig. 7. Change in membrane productivity (*j*) (1–3) and filtration coefficient (*lp*) (4–6) depending on the volume of the selected permeate when filtering sodium sulfate solutions with initial concentrations in sulfates, mg/dm^3: 1, 4 – 20; 2, 5 – 100; 3, 6 – 1000. The total volume of filtered solutions is 11 dm^3, the volume of permeate samples is 1 dm^3

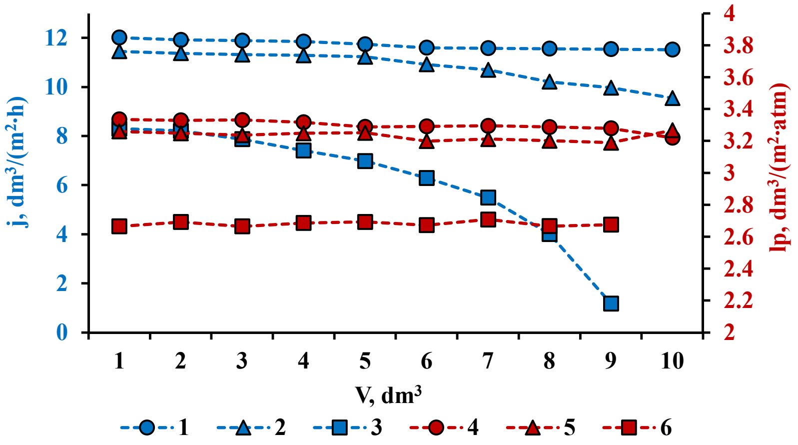

Fig. 8. Changes in membrane productivity (*j*) (1–3) and filtration coefficient (*lp*) (4–6) depending on the volume of selected permeate when filtering sodium chloride solutions with initial chloride concentrations, mg/dm^3: 1, 4 – 20; 2, 5 – 100; 3, 6 – 1000. The total volume of filtered solutions, 11 dm^3; the volume of permeate samples is 1 dm^3

Table 1

The dependence of working (Pp), osmotic (π) pressure, and pressure in the system (P) on the concentration of sodium sulfate in water at a given installation performance (q) at a permeate selection degree of 50 %

No. of entry	j, $dm^3/(m^2h)$	q, dm^3/h (dm^3/day)	$\left[SO_4^{2-}\right]$, g/dm^3	π, atm	Pp, atm	P, atm
1	8.93	2.08 (50)	1.0	0.892	2.628	3.160
2			2.0	1.784	2.628	4.052
3			3.0	2.676	2.628	4.944
4			4.0	3.518	2.628	5.786
5			5.0	4.460	2.627	6.728
6			6.0	5.352	2.637	7.620
7			7.0	6.244	2.627	8.512
8			8.0	7.036	2.627	9.298
9			9.0	8.028	2.627	10.548
10			10.0	8.920	2.627	11.547
11	13.77	4.17 (100)	1.0	0.892	4.052	4.944
12			2.0	1.784	4.052	5.836
13			3.0	2.676	4.052	6.728
14			4.0	3.518	4.052	7.570
15			5.0	4.460	4.052	8.512
16	20.83	6.25 (150)	1.0	0.892	6.131	7.023
17			2.0	1.784	6.131	7.915
18			3.0	2.676	6.131	8.807
19			4.0	3.518	6.131	9.645
20			5.0	4.460	6.131	10.591
21	27.77	8.33 (200)	1.0	0.892	8.172	9.064
22			2.0	1.784	8.172	9.956
23			3.0	2.676	8.172	10.878
24			4.0	3.518	8.172	11.690
25			5.0	4.460	8.172	12.632

Table 2

The dependence of working (Pp), osmotic (π) pressure, and pressure in the system (P) on the concentration of sodium chloride in water at a given productivity of the local filter (q) with a permeate selection degree of 50 %

No. of entry	j, $dm^3/(m^2h)$	q, dm^3/h (dm^3/day)	$\left[SO_4^{2-}\right]$, g/dm^3	π, atm	Pp, atm	P, atm
1	8.93	2.08 (50)	1.0	1.610	3.325	4.935
2			2.0	3.220	3.325	6.545
3			3.0	4.831	3.325	8.156
4			4.0	6.441	3.325	9.766
5			5.0	8.051	3.325	11.835
6			6.0	9.662	3.325	12.987
7			7.0	11.918	3.325	15.243
8			8.0	12.882	3.325	16.207
9			9.0	14.492	3.325	17.817
10			10.0	16.103	3.325	19.428
11	13.77	4.17 (100)	1.0	1.610	5.128	6.738
12			2.0	3.220	5.128	8.348
13			3.0	4.831	5.128	9.959
14			4.0	6.441	5.128	11.569
15			5.0	8.051	5.128	13.179
16	20.83	6.25 (150)	1.0	1.610	7.758	9.368
17			2.0	3.220	7.758	10.978
18			3.0	4.831	7.758	12.598
19			4.0	6.441	7.758	14.199
20			5.0	8.051	7.758	15.809
21	27.77	8.33 (200)	1.0	1.610	10.342	11.954
22			2.0	3.220	10.342	13.562
23			3.0	4.831	10.342	15.173
24			4.0	6.441	10.342	16.783
25			5.0	8.051	10.342	18.393
26			10.0	16.103	10.342	26.445

When desalting a solution with a sulfate content of 10 g/dm^3 with a permeate selection degree of 50 %, the osmotic pressure reaches 8.92 atm, and the pressure in the system should be at the level of 11.547 atm with a productivity of 50 dm^3/day.

As regards the purification of water from chlorides (Table 2), similar patterns were obtained but the pressure values in the system correspond to higher indicators. Thus, with a productivity of 200 dm^3/day with a degree of permeate selection at an initial chloride concentration of 10 g/dm^3, the pressure in the system should be at least 26.445 atm. In all other cases, the pressure in the system can be in the range of 4,935–19,428 atm.

6. Discussion of results of studying the effectiveness of the membrane Filmtec TW30-1812-50 in the desalting of solutions of sulfate and sodium chloride

Despite a number of advantages that centralized water supply has to provide the population with water in the required quantity and quality, this approach has serious drawbacks. First of all, it concerns the quality of water. Due to the use of worn-out water pipes made of high-length steel pipes, in most cases the water quality does not meet the existing requirements for drinking water for several characteristics. On the other hand, due to the anthropogenic load of water, some rivers and reservoirs have increased mineralization and hardness. At the same time, traditional methods of water treatment do not allow them to be significantly reduced. Therefore, quite often, especially in old high-rise buildings, the population uses local reverse osmosis installations. Such systems are quite widely represented in the market and quite successfully solve the problems of water purification. Nevertheless, quite often in some regions of coastal areas, tap waters are characterized by significant levels of mineralization and hardness. The issue is quite acute when using artesian and groundwater. In this case, the question arises – how suitable for water purification are the local installations in the market when using low-pressure reverse osmosis membranes.

It is not known how their productivity, selectivity will change depending on the quality of tap water, what pressure should be used in certain systems. To a certain extent, the answers to the questions posed are provided by our results.

Low-pressure reverse membranes in the processes of water demineralization were studied in [25–27]. In these works, attention was more focused on the selectivity and productivity of membranes at relatively low salt concentrations. In the current paper, the effectiveness of membranes at high levels of water mineralization was determined. In addition, our work proved the hypothesis that when using indicators of filtration coefficients at high values of water mineralization, it is possible to determine the operating pressures at specified levels of membrane productivity for certain ranges of salt concentrations.

Solutions of sulfates and sodium chlorides were investigated in this work because most often the increase in mineralization occurs precisely due to these salts. In addition, with increased salt content, with an increase in the degree of permeate selection, the osmotic pressure in water increases significantly, which significantly affects the parameters of the water purification process.

During the studies, the effectiveness of the extraction of sulfates and chlorides from water at residual concentrations in the permeate was determined, the selectivity of the membrane was determined with an increase in the degree of selection of permeate.

Extraction of sulfates and chlorides from water on the membrane Filmtec TW30-1812-50 occurs quite effectively (Fig. 2, 3).

The selectivity of the membrane for sulfates reaches 95–99 % with a higher value of the indicator at high initial concentrations of solutions. A radical change in the selectivity of the membrane for sulfates with an increase in the degree of selection of permeate was noted for small (20 mg/dm^3) initial concentrations of sulfates in the solution.

As for chlorides, in contrast to the results reported in work [6], in our paper it was determined that the membrane provides effective removal of chlorides in a wide range of concentrations. At low chloride concentrations (20–100 mg/dm^3), the membrane selectivity reaches 76–80 %. With an increase in chloride concentrations in concentrates to 100–800 mg/dm^3, the selectivity reaches 94–96 %. And at chloride concentrations higher than 1000 mg/dm^3, the selectivity of the membrane decreases to 95–93 %. It should be noted that the residual concentration of sulfates in permeate does not exceed 120 mg/dm^3 and that of chlorides 275 mg/dm^3, which is significantly lower than the permissible level in drinking water [28].

In the present work, to control the stability of concentrate solutions, the salt content of them was determined after each sample of permeate taken and this indicator was calculated theoretically. As a rule, in studies on reverse osmotic water purification, this approach is not used [11, 12]. By the correspondence of experimental and calculated values, it is possible to judge whether or not precipitation occurs in concentrates. In addition, based on the level of mineralization of the concentrate, it is possible to determine its osmotic and working pressure at a given pressure in the system.

Fig. 4, 5 demonstrate that the compositions of concentrates on the content of sulfates and chlorides, determined experimentally and calculated theoretically, are very close for all cases. This indicates their stability in the entire range of concentrations used with an increase in the degree of selection of permeate from 10 to 90 %. According to the content of chlorides and sulfates in concentrates, the change in osmotic pressure in them was calculated with an increase in the degree of selection of permeate to 90 %. At the same time, sodium chloride solutions are characterized by higher osmotic pressure values and a greater decrease in working pressure than sodium sulfate solutions (Fig. 4, 5).

Fig. 4, 5 show that an increase in the concentration of salts in concentrates leads to a decrease in working pressure. For this reason, there is a decrease in the productivity of the membrane, which corresponds to literary data [5, 8].

The effect of pressure in the system on the characteristics of the membrane can be judged by the results shown in Fig. 6. Figure demonstrates that the productivity of the membrane increases significantly with increased pressure. There was a slight decrease in working pressure with an increase in the degree of selection of permeate, which corresponds to the existing ideas [8]. However, the selectivity of the membrane with increasing pressure changed ambiguously. With an increase in pressure from 4 to 6 atm, the selectivity of the membrane increased, and with a further increase in pressure to 10 atm – decreased.

The calculation of osmotic pressures in solutions of sulfates and chlorides of different concentrations made it possible to compare the dependence of membrane productivity and the filtration coefficient at different values of the degree of selection of permeate (Fig. 7, 8). At the same time, a decrease in membrane productivity was observed with an increase in the concentration of solutions and an increase in the degree of selection of permeate, which is due to an increase in the osmotic pressure of salt solutions with an increase in their concentrations. At the same time, for solutions of sodium chloride, the osmotic pressure is greater compared to similar concentrations of sodium sulfate solutions. This is due to the highest degree of dissociation for sodium chloride, compared with sodium sulfate.

It should be noted that the data on the filtration coefficient for low-pressure reverse osmosis membranes are practically absent in numerous publications. This indicator, unlike the performance of the membrane, depends little on working pressure and can have stable values at certain concentrations of solutions. This can be seen from the data shown in Fig. 7, 8. The closest were the values of the filtration coefficient for sulfates and chlorides in the solution concentration range of 1000–7500 mg/dm^3. This is important because it makes it possible to calculate the operating pressures of reverse osmotic water purification using formula (8) depending on the concentrations of chlorides or sulfates in water when using membranes of a certain type.

Based on our results, formula (8) was used to calculate the required values of working pressure and pressure in the system at concentrations of sulfates or chlorides from 1 to 10 g/dm^3 with the performance of the cartridge with this membrane with an area of 0.2 m^2 50–200 dm^3/day. Given the high selectivity of the membrane for sulfates and chlorides, their relatively low concentrations in permeates, local installations can be used to produce drinking water. These plants will be effective even at concentrations of these salts up to 5 g/dm^3 with a permeate selection degree of up to 70 %. Restriction is possible on the pressure of water in the water supply network. The minimum pressure can be 5 atm. If it is necessary to achieve greater productivity at a salt concentration of more than 5 g/dm^3, it is necessary to use a pump with a pressure of at least 30 atm. Other initial data can be used to calculate other limiting pressures when calculating the system. This approach makes it possible to take into consideration the requirements for desalinated water, the salt content in tap or artesian water, the working and rated pressure in the reverse osmosis system, depending on the required performance of the installation.

Thus, based on the research results, the way is shown, based on the concentrations of salts, to calculate the parameters of the operation of the reverse osmosis installation, which will provide satisfactory results. That is, based on the salt concentration, it is possible to determine the performance of the installation, the osmotic pressure, the operating pressure, and the pressure in the system, which must be maintained at a given stage of permeate selection. During the operation of the installation, the user can only adjust the pressure in the system, which must necessarily be higher than the osmotic pressure.

In the future, it is advisable to advance these studies, taking into consideration the presence of hardness salts in water and the level of its alkalinity when controlling changes in the reaction of the medium (pH) in the process of water purification. The methodology used in work will reveal new or refine known aspects of the technology of membrane water purification.

7. Conclusions

1. The influence of initial concentrations of sulfate and sodium chloride on the selectivity and productivity of the reverse osmosis membrane of low-pressure Filmtec TW30-1812-50 was determined. It has been shown that the selectivity of the membrane for sulfates is higher than in chlorides and in the case of sulfates, increases with increasing initial concentrations and the degree of selection of permeate. For chlorides at initial concentrations of 1000 mg/dm^3, the selectivity decreases with increasing concentration and degree of selection of permeate. In all cases, there was a decrease in membrane productivity with an increase in the salt concentration and the degree of permeate selection.

2. It has been established that the concentrations of salts in the filtration process are constantly increasing in concentrates. To a lesser extent, the concentrations of sulfates and chlorides increase in permeate at concentrations below 1000 mg/dm^3. At concentrations of sulfates in water above 3 g/dm^3, their concentration in permeate increases to 17–97 mg/dm^3. The concentration of chlorides in permeate at initial concentrations above 1000 mg/dm^3 increases from 45 mg/dm^3 to 275 mg/dm^3 with an increase in the degree of selection of permeate from 10 % to 82 %. Increasing the concentration of salts in concentrates causes an increase in osmotic and working pressures.

3. It was shown that for solutions of sulfate and sodium chloride in the concentration range of 20–1000 mg/dm^3 with their reverse osmotic desalting on the membrane Filmtec TW30-1812-50, the filtration coefficients have constant values. For solutions of sodium chloride in the same concentration range, the filtration coefficient is 2.6–3.2 dm^3/(m^2·atm). Using the determined filtration coefficients, based on the initial concentrations of salts in water, it is possible to determine the performance of the membrane, the operating pressures in the system to obtain water of satisfactory quality.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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