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Recovery of the Properties of Spent Commercial Reverse Osmosis Membrane Elements and Ways of their Reuse

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ABSTRACT

In connection with the rapidly growing market of reverse osmosis membrane elements, particularly those intended for use in commercial water treatment installations, the problem of their regeneration and reuse has become acute. Today, the service life of such elements does not exceed 6–12 months, after which they turn into plastic waste and end up in landfills in the amount of no less than 60,000 tons per year, which leads to the emergence of serious environmental problems. This paper proposes methods and conditions for achieving almost complete restoration of the properties of used commercial reverse osmosis membrane elements by means of their regeneration and modification. The possibility of using restored elements in vending machines for filling safe physiologically complete drinking water has been demonstrated.

Keywords: reverse osmosis, regeneration, modification, reuse, plastic waste, environment.

INTRODUCTION

Today, the shortage of high-quality drinking water is one of the most urgent problems, for the solution of which reverse osmosis technology is increasingly used. By the end of 2023, the market volume of membrane reverse osmosis elements was 3.5 billion dollars [Polaris market research. 2022]. According to forecasts, its growth rate is expected to be 10% annually in the coming decade [Grossi et al., 2024a]. The latter, in turn, means a proportional increase in the number of used membrane elements, which are practically not disposed of and turn into plastic waste sent to landfills [Contreras-Martínez et al. 2021]. This situation leads to serious environmental problems.

Literature review

In reverse osmosis (RO) technology, spiral wound roll elements with thin-film composite polyamide membranes are the most common (up to 80% of the market) [Al-Naama et al., 2016]. These elements are convenient to use, transport and store. Also, they provide a high permeate flow, have significant mechanical stability, and can work in a wide range of temperature conditions (up to 45 °C) and significant pH differences (from 1 to 11) [Hailemariam et al., 2020].

Manufacturers classify reverse osmosis membrane elements according to their size, capacity, and purpose. So, membrane elements with dimensions of 8/40 (diameter/length in inches) are classified as industrial, the most common from commercial are 4/40, 4/21 and 4/14, and from household 3/12, 2/12 and 1.8/2 [Tyvonenko et al. 2022]. About 15 million different RO membrane elements are produced annually in the world, of which 10% – with a diameter of 1.8–3 inches (household), 10% – elements with a diameter of 4 inches (commercial), 80% – 8-inch elements (industrial) [Karabelas et al., 2015]. After a certain time of operation of reverse osmosis membrane elements, a decrease in their efficiency is observed due to contamination of the membrane surface, which causes the need for their replacement. Depending on the composition of the source water, membrane contamination to one degree or another includes organic, inorganic, colloidal, and biological compounds [Voutchkov 2017; Ismail et al., 2019]. To prevent membrane contamination, various methods of pretreatment of water are used [Mitchenko et al., 2021], but complete avoidance of fouling is impossible, which leads to the inevitable decommissioning of RO membrane elements and the generation of waste. One of the most effective ways to solve this problem at least partially is to restore the properties and repeatedly use membrane elements, which will prevent the reduction of the amount of potential waste [Directive 2008/98/EC, 2008].

For the elements used in industrial water treatment systems, there are regeneration technologies [Yang et al., 2013; Wang H. et al., 2023] that allow to ensure their service life up to 5–8 years. For 1.8–3-inch diameter membrane elements used in household and commercial systems, single use with a service life of about 6–12 months is typical. In the case of commercial elements, this leads to the formation of about 60 thousand tons of plastic waste annually. Industrial membrane elements are usually used for the purification and demineralization of brackish and sea water in high-performance installations. They are operated strictly in accordance with regulatory requirements in automatic mode with a high level of digitalization under the management of highly qualified personnel. This makes it possible to effectively carry out regeneration processes of membrane elements and to use them repeatedly.

Elements of the commercial series are most often used in installations for further purification of plumbing water for collective use - vending water machines, devices for making coffee, filter installations for public catering establishments, schools, medical institutions, laboratories, etc. These installations are serviced by service departments according to certain schedules, which do not always correlate with the real situation. The conditions of their operation are significantly different from industrial ones due to the reduced level of automation, control, and the ability to manage the process. These circumstances served as an obstacle to the organization of the process of regeneration of spent elements and their reuse. However, digitalization of commercial water treatment processes [Mudryk et al., 2023] has recently gained significant development, which should simplify and facilitate the implementation of the regeneration process of spent membrane elements. Household elements are used in installations for home use, where the service is reduced to the replacement of elements after a certain period of operation, regardless of the degree of their wear out. It is obvious that the regeneration of elements must be carried out centrally, which is associated with certain organizational and logistical difficulties.

There are two main methods of cleaning membrane elements: physical and chemical. Physical cleaning is usually used to remove a loose layer of colloidal foulants by rapidly backwashing the membrane with water. For chemical cleaning, it is important to choose a reagent according to the type of contamination. Alkaline solutions are used to remove biological fouling and organic contaminants, acidic solutions are used to remove inorganic contaminants (scaling). In some cases, chelating reagents are also used, for example, a solution of ethylenediaminetetraacetic acid to remove metal oxides [Jafari et al., 2020]. The effectiveness of chemical cleaning of membrane elements depends on the degree of their exhaustion (elements, the residual capacity of which is not less than 70% of the starting one are subject to regeneration [Adel et al., 2022]), the composition of regeneration solutions, temperature, and reagent flow rate. The use of these methods makes it possible to significantly extend the service life of membrane elements, which contributes to a significant reduction in the amount of waste.

The existing technologies used for the regeneration of elements of industrial purpose cannot be scaled for the regeneration of commercial and household elements due to their structural and chemical differences, as well as different operating conditions. Therefore, the development of methods for restoring the properties of spent reverse osmosis elements for commercial purposes is very relevant. According to the latest data, the most effective method of extending the service life of spent reverse osmosis membrane elements is their regeneration and/or modification to transform them into elements with a given rejection [Tyvonenko et al., 2023a], nano- or ultrafiltration [Grossi et al., 2024b; Lawler et al., 2012]. The purpose of this work is to study the processes of regeneration and modification of spent reverse osmosis membrane elements for their repeated multiple use in commercial water treatment installations.

Objects and methods of research

The objects of the research were new, spent during operation, regenerated and modified spiral wound reverse osmosis polyamide membrane elements CSV3012-500 GPD with a TU-14 membrane sheet (Source Water, China) manufactured by ECOSOFT SPC LTD (Ukraine) [Ecosoft. 2023]. The main characteristics of the new elements are listed in Table 1.

The elements were used in water vending machines [Mudryk et al., 2023] to obtain drinking-quality water from the water supply network of Kyiv city (Ukraine), the average quality indicators of which are shown in Table 2. Spent membrane elements for research were provided by the company ECOSOFT SPC LTD, which services the network of water vending machines in Kyiv. Samples were provided from 5 different locations. Before testing, the used membrane elements were preserved in a solution of sodium metabisulfite (1%) (Chemico Group, China) and glycerol (5%) (Miranda-S, Ukraine). Determination of capacity and rejection of spent, regenerated, and modified membrane elements was carried out on a special stand, which is described in work [Tyvonenko et al., 2023a]. The tests were carried out using plumbing water from Kyiv city at a temperature of 25 °C. The average composition of water is given in Table 2.

As criteria for comparing the change in capacity of spent and regenerated elements in relation to the starting characteristics of new elements, the α and β indicators are used, calculated according to empirical Equations 1 and 2. As criteria for comparing the change in rejection of spent and regenerated elements in relation to the starting characteristics of new elements, given in Table 1, the indicators γ and δ are used, which are calculated according to empirical Equations 3 and 4, respectively.

$$\alpha = \frac{Q_s}{78.8} \times 100\% \quad (1)$$

$$\beta = \frac{Q_r}{78.8} \times 100\% \quad (2)$$

$$\gamma = \frac{S_s}{95} \times 100\% \quad (3)$$

$$\delta = \frac{S_r}{95} \times 100\% \quad (4)$$

where: α – relative capacity of the spent membrane element, as a share of the starting capacity of the new element, %; β – relative capacity of the regenerated membrane element, as a share of the starting capacity of the new element, %; γ – relative rejection of the spent membrane element, as a share of the starting rejection of the new element, %; δ – relative rejection of the regenerated membrane element, as a share of the starting rejection of the new element, %; Q_s – capacity of the spent membrane element, m^3/h; Q_r – capacity of the regenerated membrane element, dm^3/h; S_s – rejection of the spent membrane element, %; S_r – rejection of the regenerated membrane element, %. 78.8 – starting capacity of the new membrane element CSV3012-500 GPD, dm^3/h; 95 – average starting rejection of the new CSV3012-500 GPD membrane element, %.

The characteristics of spent membrane elements are given in Table 3. For the regeneration of used membrane elements, special reagents produced by ECOSOFT SPC LTD were used for the regeneration of industrial membrane elements, namely

Table 1. Characteristics of new reverse osmosis membrane elements CSV3012-500 GPD

Membrane element	Diametr, inches (mm)	Lenght, inches (mm)	Initial capacity, dm^3/h	Initial rejection, %
CSV 3012 500 GPD	3 (76)	12 (305)	78.8 ± 20%	94–96

Table 2. Average values of indicators of plumbing water quality in Kyiv for 2023 [Driker Yu., 2023]

Indicator	Average value	Maximum value	Minimum value
Dry residue, mg/dm^3	293.8	310.4	277.2
Hardness, mg-eq/dm^3	4.2	4.6	3.8
Total iron. mg/dm^3	0.2	0.3	0.1
Permanganate oxidizability, mgO$_2$/dm^3	5.9	6.0	5.7
Chromaticity, deg.	35.0	36.0	34.0

Table 3. Characteristics of used reverse osmosis membrane elements CSV3012-500 GPD provided for research

No.	Time of use, days	Volume of permeate during the time of use, dm^3	Q_s, dm^3/h	α, %	S_s, %	γ, %
1	34	17590	34.0	43.1	95.0	100.0
2	41	23995	36.4	46.1	81.2	85.5
3	57	26363	27.3	34.6	90.1	94.9
4	79	32763	20.9	26.6	96.8	101.9
5	120	55561	16.5	20.9	86.5	91.1

the alkaline solution Ecoclean 211 and acid Ecoclean 203, as well as the solution of sodium hypochlorite (> 30%) produced by the company "Milam" (Ukraine). The process of regeneration of spent reverse osmosis membrane elements was carried out on the installation, Figure 1.

The regeneration solution contained in the tank 2 is fed to the low-pressure pump, after which the solution is directed through the manometer 3 (to control the pressure before the filter) and the temperature sensor 4 to the mechanical filter 5, with a filtration rating of 5 µm. Next, the regeneration solution passes through the manometer 6, which is used to set the necessary pressure during regeneration, and goes to the membrane holder 7, in which the membrane element is installed. Permeate and concentrate after the membrane element are returned to tank 1.

The regeneration process was carried out in three consecutive stages: alkaline, acidic, and oxidative. The characteristics of the solutions used at each of these stages are presented in Table 4. During regeneration, the following modes were used:

- soaking the element in a regeneration solution at a temperature of 25 °C without recirculation to soak impurities on the surface of the membrane;
- slow washing, which allows to speed up and deepen the penetration of the regeneration solution into the membrane and increase the soaking of impurities. It is carried out at a temperature of 25 °C and a pressure of 0.5 bar;
- fast washing – ensures the removal of impurities from the surface of the membrane after soaking and slow washing (pressure – 3 bars).

After each stage of regeneration, the characteristics of the membrane elements were determined. For a visual evaluation of the efficiency of the regeneration process, an autopsy of the spent and regenerated membrane elements was performed. Photographs of the surface of the membranes were obtained using a Nikon D70S camera (Japan), photomicrographs were obtained using a Trek DCM510 camera with a RL05-48 ring diode illuminator on an optical microscope (PZO, Poland).

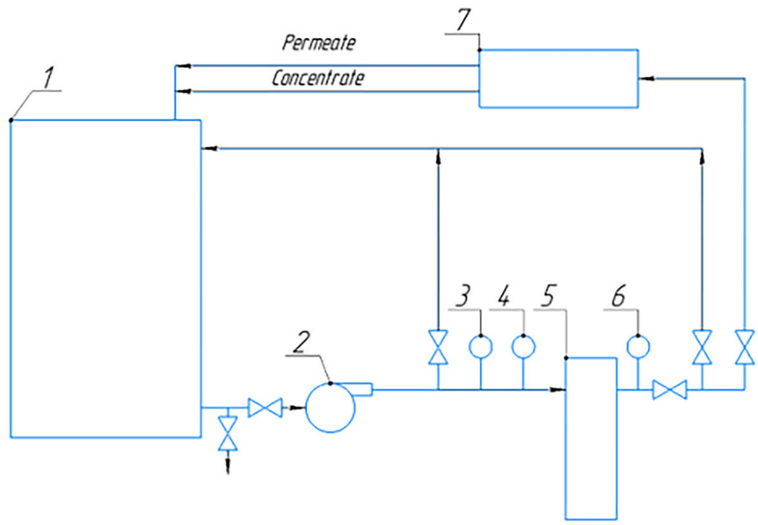

Figure 1. Schematic diagram of the installation for the regeneration of used reverse osmosis membrane elements. 1 – tank; 2 – low-pressure pump; 3 – manometer; 4 – thermometer; 5 – mechanical filter (filtration rating 5 µm); 6 – manometer; 7 – membrane holder

Table 4. Characteristics of solutions used for regeneration of membrane elements

Stage of regeneration	Reagent	Concentration of solution	pH	Temperature, °C
Alkaline	Ecoclean 211	2%	11.1	25–30
Acidic	Ecoclean 203	2%	2.3	25–30
Oxidative	NaClO	1.65 g/dm^3 (active chlorine)	10.1	25–30

To determine the chemical composition of fouling on spent and regenerated membrane elements, segments of membrane sheet of specified sizes were soaked separately in a solution of 5% NaOH (Merck, Germany) and 5% HCl (Lachema, Czech Republic) for 1 day. In alkaline solutions, the content of silicates [GOST 26449.1-85. 1987] and organic substances [DSTU ISO 8467:2021. 2021] was determined and in acidic solutions - the content of total iron and hardness ions [DSTU ISO 6332:2003. 2004; DSTU ISO 6059:2003. 2003]. According to the obtained data, the pollution content per unit of surface area ε Eq. 5 and the degree of pollution removal were calculated.

$$\varepsilon = \frac{C_e \times V_s}{S_p} \tag{5}$$

where: ε – the content of the polluting component per unit of surface area, mg/m^2 (mg-eq/m^2); C_e – the concentration of the polluting component in the alkaline or acid solution, mg/dm^3 or mg-eq/dm^3; V_s – volume of alkaline or acid solution, dm^3; S_p – the area of the investigated sample of the membrane fabric, m^2.

To modify the regenerated element, a solution of sodium hypochlorite with a certain concentration of active chlorine and pH 10 was used. The modification time was 24 hours, and the temperature was 25 °C. The modification process was carried out in passive conditions [Gu et al., 2012; Antony et al., 2010], which involves immersing the membrane element for a certain time in a hermetic container with a solution of sodium hypochlorite. The dose of active chlorine acting on the membrane element during modification was determined by Eq. 6:

$$N = C_{Cl} \times \tau \tag{6}$$

where: N – the dose of active chlorine, (mg/dm^3)h; C_{Cl} – concentration of active chlorine, mg/dm^3; τ – contact time, h.

After the modification, the membrane elements were washed from the active chlorine solution by passing demineralized reverse osmosis water through the membrane elements for at least 30 min, until the absence of reaction to active chlorine in the permeate and concentrate was achieved. After washing, the elements were kept in a stabilization solution [Tyvonenko et al., 2023a]. To stabilize the modified membrane elements, solutions of sodium metabisulfite (1%) and glycerol (5%) were used [Maeda 2022].

Pilot tests of regenerated and modified membrane elements were carried out using water vending machines connected to the plumbing water of Kyiv city, at an average temperature of 6–8 °C and a pressure of 5.2–5.7 bar.

RESULTS AND DISCUSSION

The dependence of the relative indicators of capacity (α) and rejection (γ) of spent membrane elements on the volume of permeate, which was obtained during the operation of elements in vending machines for filling water was found (Figure 2). As can be seen from Figure 2, when the volume of the obtained permeate increases from 0 to 55,000 dm^3, the relative capacity of the element, characterized by the α indicator, decreases significantly – from 100 to 20%, respectively. This happens because of an increase in the layer of pollution on the surface of the membrane sheet, which affects the drop in the capacity of the membrane element. At the same time, the rejection of the elements (indicator γ) almost does not change. Figure 3 shows the change in the relative capacity (indicator β) of the elements after each stage of regeneration (alkaline, acid, and oxidizing) in comparison with the relative capacity of the spent element (indicator α).

From Figure 3, it can be concluded that the capacity of used membrane elements increases after each of the stages of regeneration, as evidenced by the increase in the value of the β indicator. Regeneration is considered successful when a value of β > 80% is reached (see Table 1). As can be seen from the given data, this condition is fulfilled for elements No. 1–3, for which the β

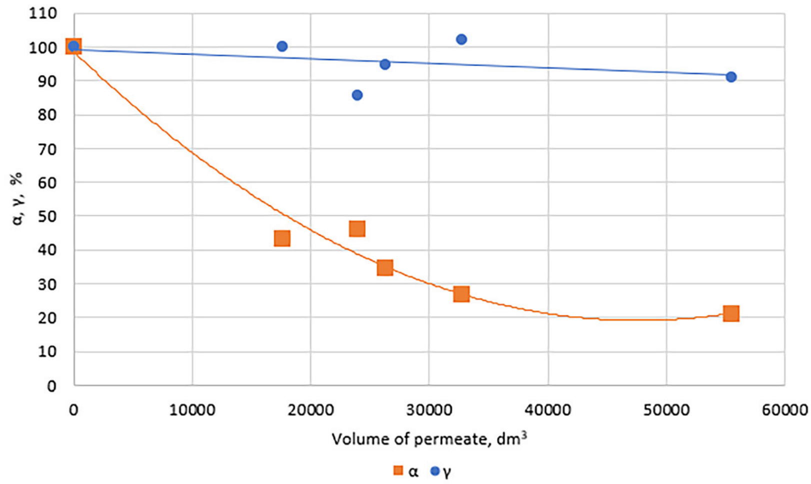

Figure 2. The dependence of the relative indicators of capacity (*α*) and rejection (*γ*) of spent membrane elements on the volume of permeate, which was obtained during the operation of elements in vending machines for filling water

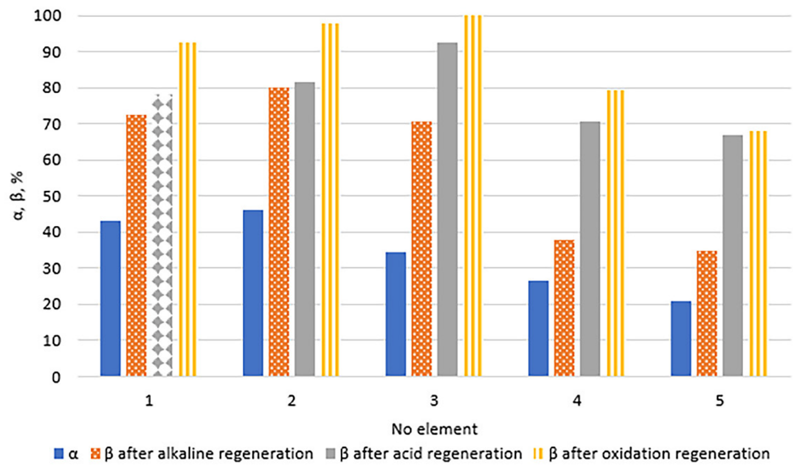

Figure 3. The change in β indicators after different degrees of regeneration compared to the values of α indicators of spent elements

indicator is 90–100%, and the α indicator exceeds the value of 30%. For a more visual assessment of the efficiency of the regeneration process, an autopsy of membrane elements No. 2 and 4 was performed before and after regeneration. Photographs and micrographs of the surface of the membranes are shown in Figures 4(a, b, c), and the chemical composition of fouling is shown in Table 5. Figure 4b shows that the membrane sheet of the regenerated element No. 2 looks practically clean, without signs of contamination, which correlates with the data on the almost complete restoration of its characteristics after regeneration (β = 97.8%). At the same time, the presence of a small layer of pollution on the surface of the membrane sheet of element No. 4 (Fig. 4c) confirms that the regeneration of this element was less successful (β = 79.2%). It is logical to connect this with the difference in the values of the α indicator for these elements (Table 2), which characterizes the degree of their wear out.

Information on the chemical composition of fouling on the surface of membrane sheet of spent and regenerated elements is given in Table 5. As can be seen from the above data, the surface of spent element No. 4 contains a significantly larger amount of all types of pollution than on the surface of spent element No. 2, which is explained by the different volume of permeate that was obtained from them during operation (Table 3). However, as can be seen, the regeneration took place with a high percentage of removal of the main pollutant

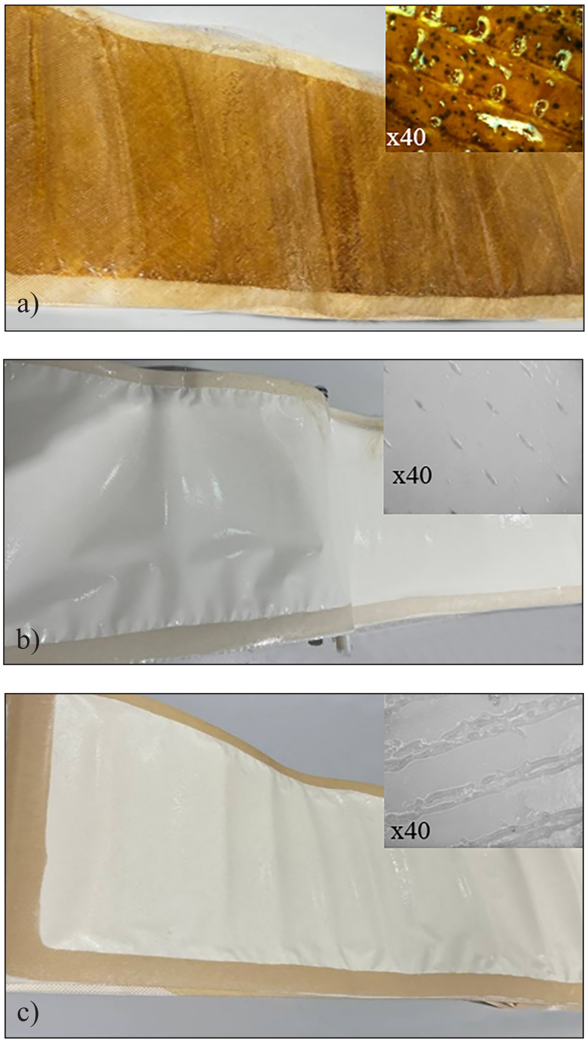

Figure 4. Photographs and microphotographs of the membrane sheet of elements No. 2 spent (a) and regenerated (b), No. 4 regenerated (c)

components from the surface of the membranes of both elements, but with a clear advantage for element No. 2 in terms of all pollutants.

Figure 5 shows the dependence of the relative indicators of capacity β and rejection δ on the volume of permeate obtained during the operation of elements in vending machines for drinking water, the composition of which is given in Table 2. As can be seen from the data presented in Figure 5, the desired degree of restoration of the characteristics of spent elements as a result of regeneration (β > 80%, δ–100%) is achieved if the volume of the obtained permeate does not exceed 32,000 dm^3. That is why regenerated elements No. 1–3, which meet these conditions, were selected for further research.

To compare the capacity and rejection values of the regenerated membrane elements and the starting characteristics of the new membrane element CSV3012-500 GPD, they were tested under the same conditions on plumbing water of Kyiv city. The test results are shown in Figure 6, and more detailed information about the quality of purified water is in Table 6. As the results of the experiment showed, the capacity and rejection values of all regenerated membrane elements were identical to the corresponding starting characteristics of the new element. The capacity of the elements was 56–61 dm^3/h, and the rejection was 96–97%. Table 6 shows the composition of the permeate obtained using regenerated membrane elements No. 1, 2, 3 and a new membrane element, and their comparison with the requirements for physiologically complete water [Ministerstvo Okhorony Zdorovia Ukrainy. 2010].

The analysis of the data presented in Table 6 shows that the composition of the permeate, which was obtained using regenerated and new membrane elements, is practically identical, and in all cases meets the requirements for safe, but not physiologically complete water. In order to achieve the established norms, it is necessary either to carry out demineralization of the obtained permeate, or to use modified membrane elements. At the next stage of the work, the regeneration membrane elements were modified according to the method proposed in

Table 5. Chemical composition of fouling on the surface of membrane sheet of spent and regenerated elements

Fouling component	Element No. 2			Element No. 4		
	Spent	Regenerated		Spent	Regenerated	
	Amount of pollutant	Amount of pollutant	Degree of fouling removal, %	Amount of pollutant	Amount of pollutant	Degree of fouling removal, %
Silicates, mg/m^2	2986.4	131.0	95.6	3981.9	235.3	93.6
Organic compounds, mg/m^2	443.2	63.6	85.6	599.5	150	75
Total iron, mg/m^2	919.9	5.2	99.4	1210.4	9.7	99.2
Hardness, mg-eq/m^2	51.2	3.4	93.4	67.8	6.8	90.0

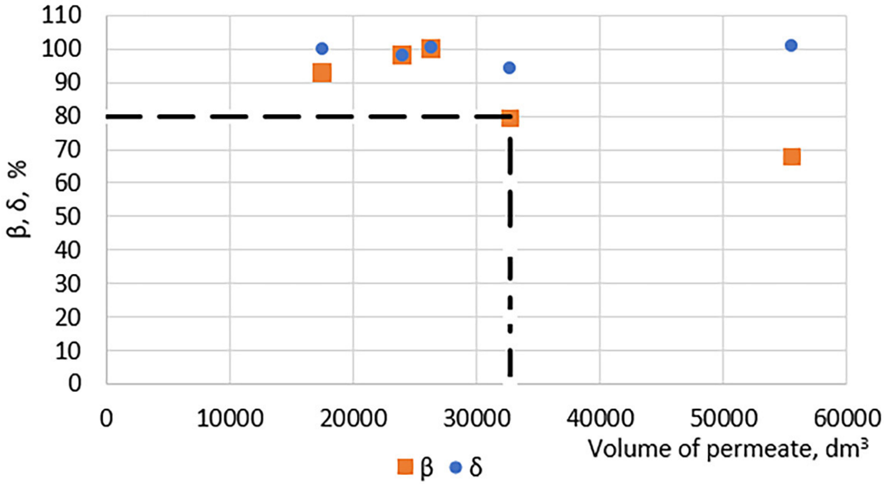

Figure 5. Influence of the volume of permeate obtained during the operation of the elements on the values of the relative indicators of capacity β and rejection δ

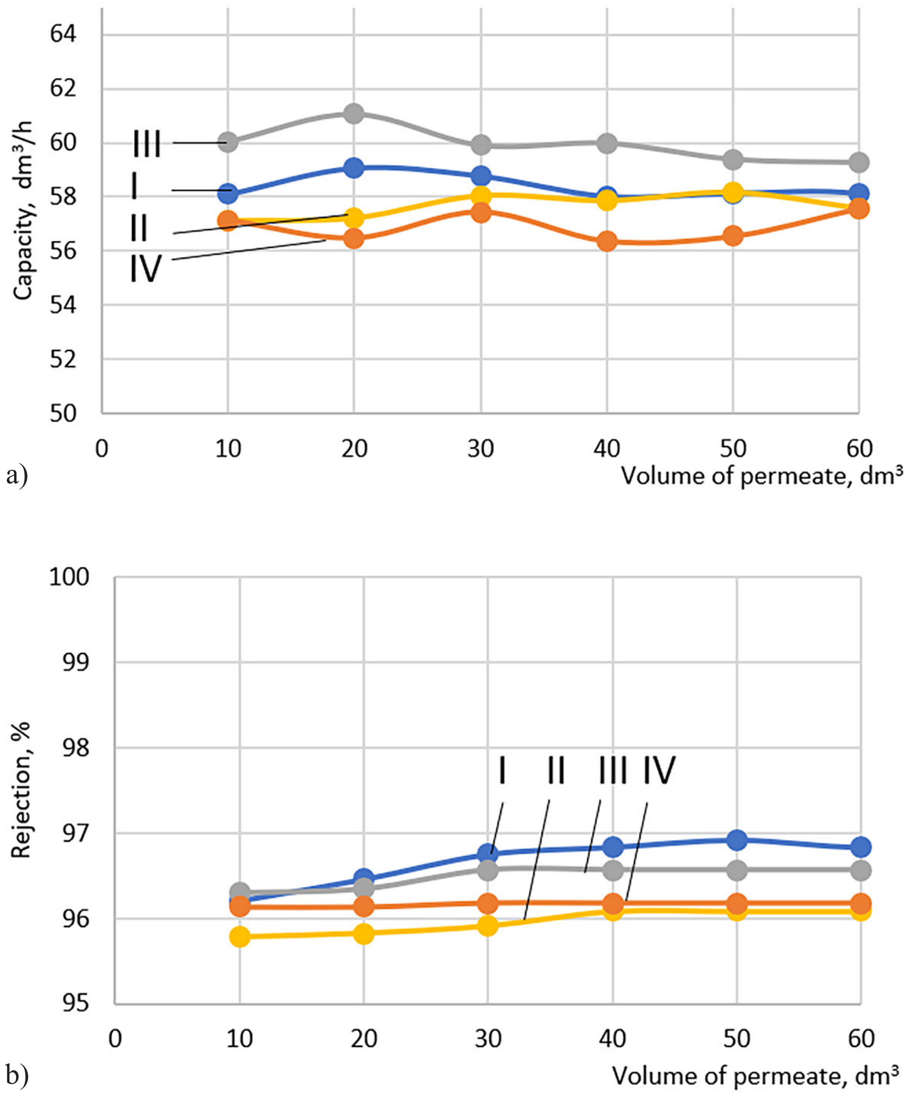

Figure 6. Characteristics of new and regenerated membrane elements, obtained during their testing on plumbing water of Kyiv city at a temperature of 6 ºC. a) - capacity, b) – rejection (I – new element; II – regenerated element No. 1; III – regenerated element No. 2; IV – regenerated element No. 3)

Table 6. Composition of permeate obtained from regenerated membrane elements No. 1, 2, 3 and a new membrane element and requirements for safe physiologically complete water according to [Ministerstvo Okhorony Zdorovia Ukrainy, 2010]

Characteristics	Regenerated elements			New membrane element	Requirements according to [Ministerstvo Okhorony Zdorovia Ukrainy, 2010]
	No. 1	No. 2	No. 3		
Salt content, mg/dm³	9.0	8.0	9.1	7.2	≥ 100
pH	6.35	6.05	6.16	5.91	6.5–8.5
Hardness, mg-eq/dm³	0.25	0.25	0.25	0.25	≥ 1
Chromaticity, deg.	0	0	0	0	≤ 20
Content of trihalomethanes (THM), μg/dm³	≤ 5	≤ 5	≤ 5	≤ 5	≤ 100
Total microbial count, CFU/cm³	0	0	1	0	≤ 50

[Tyvonenko et.al., 2023b] in order to use them in the process of obtaining safe physiologically complete water. The dependence of the change in rejection of new and regenerated membrane elements on the dose of active chlorine used during their modification is shown in Figure 7. The analysis of the given data suggests that the mode that was proposed for the modification of new membrane elements can also be used for the modification of regenerated ones. At the same time, a regenerated modified element with a rejection of no more than 60% should be used to obtain safe, physiologically complete water from the plumbing water of Kyiv city. Figure 8 shows a comparison of the characteristics of the regenerated and regenerated modified membrane element, established during the pilot tests of Kyiv city plumbing water purification process at a temperature of 6 °C. The analysis of the obtained results showed that the modification of the regenerated commercial membrane element allowed to increase its capacity from 56–61 dm³/h to 100–110 dm³/h and to reduce its rejection from 95% to 43 ± 3%, which led to an increase in the salt content of the permeate and ensured its retention at the level of 130 ± 5 mg/dm³ during the entire test period. Table 7 shows the quality indicators of the permeate obtained after the regenerated modified element and the corresponding normative values.The analysis of the results in Table 7 showed the fundamental possibility of obtaining permeate with quality indicators that meet the requirements for safe, physiologically complete water, using a regenerated

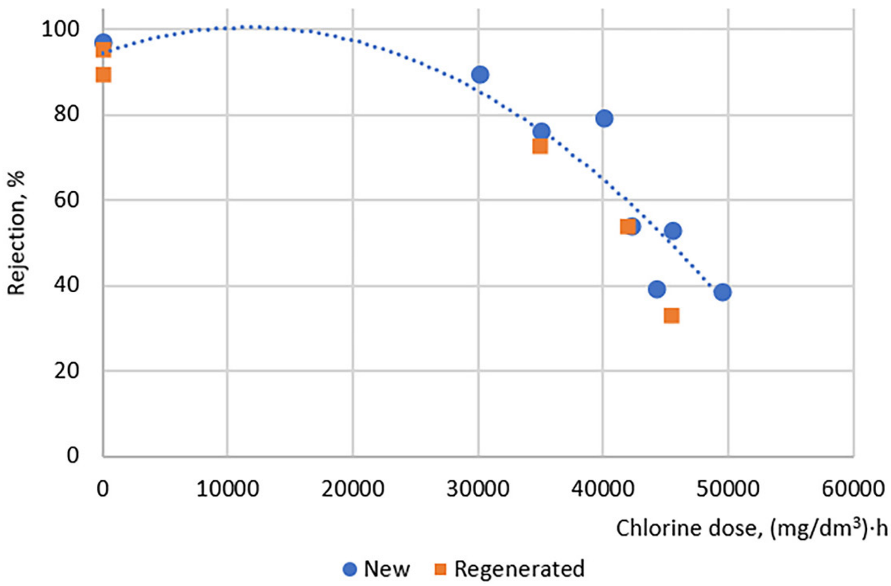

Figure 7. Dependence of the change in rejection of new and regenerated membrane elements on the dose of active chlorine during their modification

Table 7. Permeate quality indicators obtained after the regenerated modified element and corresponding normative values

Volume of permeate, dm³	50	100	200	400	600	800	1000	Requirements [Ministerstvo Okhorony Zdorovia Ukrainy, 2010]
Temperature, °C	6.5	6.0	6.2	5.8	5.5	5.5	6.0	
pH	7.3	7.3	7.3	7.4	7.4	7.4	7.5	6.5–8.5
Hardness, mg-eq/dm³	2.4	2.5	2.6	2.5	2.5	2.5	2.4	≥ 1
Chromaticity, deg	0	0	0	0	0	0	0	≤ 20
Content of trihalomethanes (THM), µg/dm³	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 100
Total microbial count, CFU/cm³	2	0	0	1	0	2	0	≤ 50

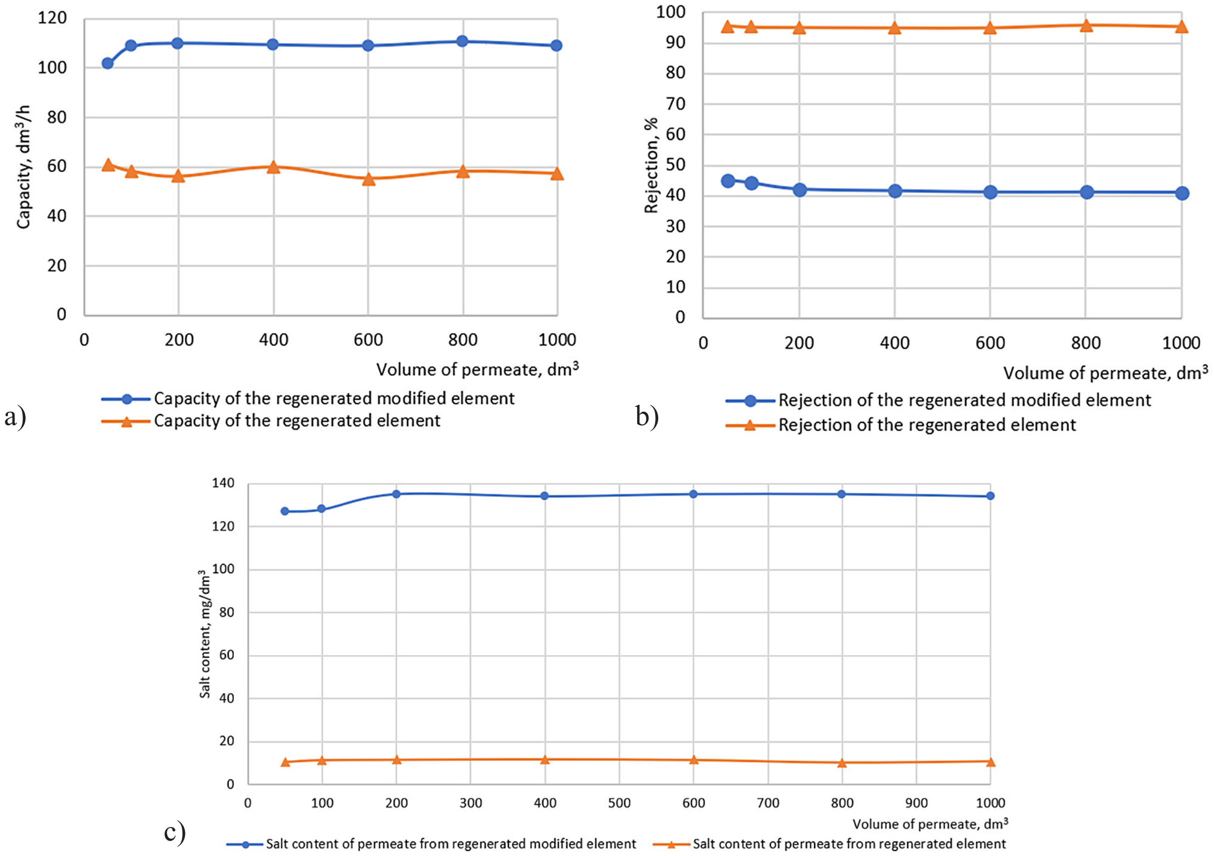

Figure 8. Comparison of the characteristics of regenerated and regenerated modified membrane elements obtained during pilot tests: a) capacity, b) rejection, c) salt content

modified membrane element. Further research will be aimed primarily at determining the resource of regenerated and regenerated modified commercial membrane elements and the conditions of their multiple use.

CONCLUSIONS

The possibility of regeneration of reverse osmosis membrane elements of commercial size by three-stage treatment with alkaline, acid, and oxidizing solutions has been established. It is shown that the efficiency of regeneration depends on the degree of exhaustion of the membrane elements. Achieving the capacity of regenerated elements at the level of 80–100% of the starting capacity of new elements is possible when the level of relative capacity of spent elements entering for regeneration is at least 30% of the starting capacity of new elements. For Kyiv city plumbing water, this condition is met when no more than 32,000 dm^3 of permeate is obtained from the element. The obtained results are described by empirical equations that can be adapted for specific membrane elements.

The results of pilot tests conducted using water vending machines showed that regenerated membrane elements can be reused as reverse osmosis ones in commercial water treatment installations. The composition of the permeate obtained when using regenerated elements does not differ from that obtained using new elements. The quality indicators of the permeate obtained in both cases meet the requirements for safe drinking water, but not for physiologically adequate water. Modification of regenerated reverse osmotic membrane elements was carried out by passive treatment with sodium hypochlorite solution. It was found that the properties of regenerated modified membrane elements coincide with the properties of new membrane elements modified under similar conditions. The possibility of obtaining safe, physiologically complete drinking water from the water supply network of Kyiv city when using regenerated modified membrane elements in water vending machines has been established.

Implementation of the proposed technology of regeneration and modification of spent reverse osmosis elements will allow them to be reused in commercial water treatment installations and, accordingly, to reduce the volume of produced plastic waste, which means to improve the environmental assessment of the reverse osmosis method itself.

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